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DESIGN HANDBOOK FOR OPTICAL FIBER SYSTEMS,(U)
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LEVEL II

DESIGN HANDBOOK

FOR

OPTICAL FIBER SYSTEMS

AUGUST 1978

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COMMUNICATIONS ENGINEERING DIRECTORATE

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FOREWORD

This handbook was prepared for the US Army Communications-Electronics Engineering Installation Agency to provide our communications engineers with the background, data, concepts, typical equipment parameters, design methods, tradeoff considerations and evaluation methodology required to design, evaluate or specify a fiber optic communication system. It was specifically written for a communications engineer or specialist who has little or no experience in the fiber optic technology.

Basic introductory material is provided to develop a common baseline of fiber optic theory. From here the material is tailored to provide the necessary and fundamental information and techniques required to design, specify or evaluate a fiber optic system. Specific emphasis is placed on providing only the essential information required for an application engineer/specialist to perform his work. A list of references is provided for those who wish further information on the optical fiber theory and technology.

TABLE OF CONTENTS

TABLE OF CONTENTS (CONT.)

TABLE OF CONTENTS (CONT.)

LIST OF FIGURES

LIST OF FIGURES (CONT.)

LIST OF FIGURES (CONT.)

LIST OF FIGURES (CONT.)

LIST OF FIGURES (CONT.)

LIST OF FLOW CHARTS

LIST OF TABLES

DESIGN HANDBOOK FOR OPTICAL FIBER SYSTEMS

R.W. Hubbard
R.L. Gallawa*

This document has been prepared as a handbook applicable to the design and performance evaluation of optical fiber communication systems. It is oriented toward the communication engineer who is familiar with microwave systems (both cable and propagating), but who has had little or no experience in the fiber-optics technology.

Introductory material for all of the components currently being applied to this new communications technology has been included, together with a discussion of the most important operational parameters and considerations. Contents of the text material have been limited by using a "need to know" concept in order to provide the user *with only* the necessary and fundamental information.

Design methods are presented in detail, and are coupled with illustrative examples. The methodology presented should be useful as a guideline either to the design and specification of a system, or to evaluate a proposed design to meet specified operational requirements.

Key words: fiber waveguides; optical detectors; optical-fiber communications; optical source; microwave communications.

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CHAPTER 1

INTRODUCTION AND SCOPE

1-1. GENERAL INTRODUCTION

The application of optical frequencies as a communications carrier has grown over many decades, from the simple visible signalling light to sophisticated systems that use highly coherent sources to propagate through the atmosphere. Such systems however, are severely limited in their range and availability by an environment that is quite hostile to effective propagation.

In recent years, the ability to use light as a communications carrier has been advanced tremendously with the development of a practical guided-wave technology. The techniques used for this new communication method have many similarities to those used by communication engineers in the microwave frequency bands. For example, waveguide technology at these lower frequencies has been understood and applied for some time. Losses in both waveguides and coaxial cables have been reduced through the years, and other transmission characteristics improved. However, every practicing engineer knows (almost by intuition) the limits of practicality of using guided waves in systems at these frequencies. Guides themselves are expensive, generally bulky, and the significant losses are usually specified in increments of meters. Thus, their application is usually limited to short distances (generally less than a few hundred meters). For point-to-point communications in microwave systems, the designer must either include many necessary repeaters to span the desired distance, or terminate the guided-wave system at a practical point and convert to a propagation domain.

The communications engineer is also quite familiar with the host of problems associated with microwave propagation. These begin with distance (line-of-sight (LOS) or beyond the horizon) considerations, and the mechanical implementation associated with each of these. For LOS links he must consider terrain profiles, expected weather conditions, tower heights, antenna size, length of feeder guides, power budgets, interference potential--the list

goes on. Similarly, for circuits beyond the radio horizon, he must consider most of the above factors, coupled with even more complex space and/or frequency diversity configurations to improve performance through the transmission medium. No small problem associated with these designs is the sheer bulk of the required hardware (large reflecting-type antennas, towers, equipment shelters), and the real estate and access necessary to support the installations. The complexity of the design procedures required for these microwave systems, and the complete scope of considerations has been presented in a handbook prepared by the Institute for Telecommunication Sciences (ITS) in Boulder, Colorado for the U.S. Air Force. The handbook is proposed for publication by the military sponsor as a tri-service resource (MIL-HDBK-416).

1-2. PURPOSE

The purpose of the present handbook is to provide the communication engineer, who is already familiar with the microwave systems as noted above, an initial set of skills and directions for the new technology of optical guided-wave communication systems. We shall assume that the user of this handbook has had limited prior experience with optical systems, and in his design work does not have the time or absolute need to become familiar with the underlying developments that have advanced the state-of-the-art. We shall attempt here to bring into succinct focus only those aspects of this new technology that the design engineer will need to apply, and to limit these aspects in depth to a practical understanding of concepts and operational functions. Wherever possible, this purpose will be aided in pointing out correlativity with familiar microwave design aspects so that maximum advantage may be made of more familiar design criteria.

1-3. APPLICATION AND SCOPE

It is anticipated that this handbook will be found useful to the practicing communications engineer to bridge-the-gap between microwave systems and optical guided-wave systems in a number of communication areas. It has been our intent in the

preparation of the handbook, and in selecting the included technical material, to provide a document which is as near to a single-source reference for the designer as possible. In the complex technology of fiber optics we obviously cannot cover all technical subjects in great detail within this report. We are, therefore, including a comprehensive bibliography to enhance the scope and depth of the handbook. To assist in introducing the unfamiliar user to the optical communications art, a Glossary of Terms has also been added. The glossary is limited to the terms and definitions deemed necessary for the practical designer to know, and the definitions themselves are framed in an applications sense rather than in a physical sense whenever practical.

Two additional publications of ITS are considered as companion documents to this handbook if additional information is desired. These are:

1. A User's Manual for Optical Waveguide Communications (Gallawa, 1976), and
2. Design Curves for Optical Waveguide Digital Communication Systems (Gallawa, 1974).

Selected or updated excerpts from these publications are used in the handbook to provide examples of application. However, the reader is encouraged to make use of the more in-depth treatment presented in these companion documents. In general, the first presents a fairly extensive summary of the optical communications field in fiber waveguides, and a nonmathematical development of design curves and tables of practical value. The second document encompasses the area of cost factor analyses and results applicable to design considerations.

The scope of the present handbook does not include system cost considerations. The emphasis is placed on the technical configurations and performance of systems using state-ofthe-art components. Some cost comparisons are included only in cases where design alternatives appear feasible, and then the comparisons are limited to estimates based on component costs. More comprehensive cost models are available in the above references and other cited literature.

1-4. OBJECTIVES AND ORGANIZATION

The fundamental objective of this handbook is to provide the communications engineer with a systematic guideline and approach to both the design and evaluation of an optical-fiber communication/transmission system. The distinction between communication and transmission is based on the separation of stand-alone (complete optical communication systems) and those applications where there is an existing communication system, and it is desired to substitute the optical-fiber waveguide as the transmission medium. The emphasis is on the latter situation, as this is considered the primary objective. As an example, we offer a systematic approach to be taken by the communication systems engineer to replace a microwave transmission channel with an optical fiber link, and to interface this new transmission medium with existing terminal equipments.

A word about the organization of the handbook may be helpful to the reader at this point. In keeping with the premise that the communications engineer using this manual is unfamiliar with optical-fiber technology, we first present a brief summary, which includes an outline of the advantages and disadvantages of the technique and some "framework" comparisons with the microwave technology that is assumed to be familiar material. Next, we summarize the fundamental concepts needed to begin a design task, including both the parameters and the components that the designer will encounter in the fiber-optics world.

In subsequent chapters, we examine those elements of the communications process that are common to any system, namely;

1. Modulation and multiplexing techniques.
2. System configurations and modem requirements.
3. Electro-optical interface problems and methods.

Following these, a chapter on the actual design of an optical fiber link is presented. It begins with a definition of user requirements, and conceptual design techniques. The treatment then expands into the actual design process and

implementation. Examples of these procedures are included, and options or trade-off possibilities are explored.

Performance evaluation has also been included in this chapter, illustrating areas of evaluation and measurement that are different, as well as common to optical and microwave systems. Following this chapter, three special appendices and the glossary of terms and definitions are presented.

It should be stressed that the fiber-optics communication field is relatively new and in a state of dynamic change. In this situation, there are few (if any) standards applicable to either components or measurements. The availability of components and their specifications is, however, improving rapidly. This fact has an almost continuous impact on the details of system design. Thus, in order to extend the useful life of this document to the maximum possible, the content of the basic text has been drafted in the most general terms possible, and specific details relegated to appendices. For example, component examples and parameters dealt with in Chapter 2 reflect medians of magnitude and range in the current state-of-the-art. The reader is referred to manufacturers' literature for the latest information on specific components and subsystems. Also, detailed design examples are not included in the text, but appended for the same reasons.

1-5. INTRODUCTORY COMMENTS ON OPTICAL FIBER COMMUNICATION

Perhaps the first thing that will strike the microwave communications engineer as he begins to investigate the guided-optical communications field is the drastic change in scales. For example, he has become accustomed to the physical size of terminal components such as parobolic antennas, feed horns and lines as mentioned previously. In addition, he is accustomed to thinking in terms of watts or kilowatts of power delivered to these components for radiating systems. Both of these scales (physical size and units) change significantly in the fiber-optics field. Both the transmitter and receiver elements are generally solid-state devices packaged much the same as transis-

tors, and appear extremely small. Radiated power levels are generally measured in the milliwatt range.

The second striking feature of the technology is the extremely small cross-sectional dimensions of the transmission medium--the optical fiber itself. The core diameter of these fibers is on the order of 150 µm or less for multi-mode fibers (the term multi-mode is discussed in Chapter 2). The prime advantage of the fiber as the transmission medium is recognized by the microwave engineer as having well-behaved, stable, characteristics. Being able to confine the information signal to an open waveguide, free of the transmission variations and anomalies of the microwave channel is a vista previously unknown to the microwave engineer. Familiar concepts of fade margins, space and/or frequency diversity, atmospheric absorption, rain attenuation, terrain clearance and any number of other considerations are not necessary in the optical-fiber technology. There are a few corollary parameters that are of concern in the application of the fiber waveguide, but these are generally functions of the fiber material and its dimensions, and are time invariant to first order approximations. These features of the captive medium simplify the basic system design. However, they add new dimensions in terms of electro-optic interface specifications, and new considerations involving the physical location and support of the fiber-optic cable in point-to-point communication systems. It may also require the engineer to deal with in-line repeaters and repeater spacings that are foreign to the point-to-point microwave system.

The above factors represent only the major surface differences in design. Others, less obvious at the outset, will become evident as the procedures are outlined in this document. As stated previously, however, it is our intent to emphasize similarities in these procedures rather than differences. Experience flow-through from one domain to the other is an objective.

Before proceeding to details of this new communications technology, we will briefly present the most significant advantages and disadvantages associated with it.

a. Advantages of Fiber-Optics Transmission.

1. Increased Information Capacity. The available bandwidth, and consequently the information transfer capacity, is significantly greater than for transmission cables and most microwave radio systems. Systems have been successfully implemented with digital data rates in excess of 1 G-bit/s.
2. Small Size and Light Weight. Large savings factors in both size and weight are possible compared with conventional cable systems. These can be especially significant in avionics and shipboard systems, and similarly important in trunking or data-bus applications. In microwave replacement, the size and weight elimination of terminal equipment is dramatic.
3. Electromagnetic Compatibility. Fiber-optics technology can be the solution to many severe problems in the electromagnetic environment. The fiber is relatively immune to electromagnetic interference (EMI) and noise. Also, since under normal operating conditions the fiber does not radiate, it does not create any EMI. The dielectric properties of the fiber provide electrical isolation between equipment, and thus eliminate the possibility of ground loops.
4. Security. Since signals do not normally radiate from a fiber, signal transmissions are inherently more secure from intrusions by non-authorized receivers.

5. Crosstalk. The dielectric non-radiating medium essentially reduces any likelihood of crosstalk problems between fibers. This is true regardless of data rates, cable lengths, or channel density on the fiber.
6. Safety. The fiber-optics medium provides a safety feature in hazardous areas. Since it does not radiate or create electrical sparks due to short circuits, it can be safely used in areas where metallic cables would be dangerous.

b. Disadvantages of Fiber-Optic Techniques

The technology is not without significant disadvantages. Some of those listed below are a result of the infancy of the field, and will no doubt become less significant or eliminated with future development.

1. Non-Linearities in Components. This fact limits to some degree the application for analog communications.
2. Relatively High Losses at Interfaces. Losses in the fiber, splices and connectors as well as those at the junctions of the fiber with the sources and detectors can be relatively high. These factors are being improved rapidly, however, as the industry progresses in both research and manufacturing techniques.
3. Component Life is not Well-Known. This is perhaps the most significant disadvantage today for the system designer. The life expectancy of the optical sources and detectors are not well-known. Data are beginning to appear in the literature and in manufacturers' specifications, but not to a degree to limit this concern. The common design approach currently is to degrade performance factors somewhat to compensate for this unknown.

4. Lack of Standards. There is almost a complete lack of standards in both the optical fiber and associated component areas. The void is seen in almost all elements of the technical field, from manufacturing to component specification, and in measurements. Variation in parameter size (or dimension) is, perhaps, the most significant problem faced by the designer today, as the lack of adequate standards here can restrict his options of component selection.

CHAPTER 2

OPTICAL FIBER COMPONENTS AND PARAMETERS

2-1. INTRODUCTION

Before one can approach the actual design of a communication system using the optical-fiber waveguide as a transmission medium, the fiber itself and the interface components necessary for coupling in and out of the fiber must be understood. The requirement is not unlike the knowledge that the microwave engineer needed to acquire in order to design an efficient system composed of traveling-wave tube (TWT) sources, waveguide components, connectors transducers, loads, and detectors. Each of these components has many variations or substitutes that need to be considered. For example, if the power output of a particular TWT source is not sufficient for the desired link, the engineer then must consider the alternatives of a klystron or magnetron tube. In these tradeoffs, he had to keep in mind the different characteristics, matching requirements and other application parameters peculiar to the particular source. However, it is not essential that he know the physics behind these devices or the operational details in any precise manner in order to use them effectively. The same fact is basically true in the fiber-optics area. The designer must have a comprehensive grasp of the available components and the range of the parameters of these devices that are paramount to the design application. He has only an academic need to understand the physics of a device or component. At most, he needs to know only the physical features of the item that will impact on the intended use and expected results. In the case of each component, there is a classification of basic parameters that needs to be known and understood, and a secondary classification that entails only an awareness. It is the intent of this section to present the basic parameters that are required for each component, and to call attention to the secondary considerations. The latter may be referred to other sections of this document or to other cited literature for more detailed consideration.

The transition of design concepts to the optical fiber technology can be enhanced if we exploit past knowledge and experience whenever possible, and we understand the differences that exist between conventional and optical techniques (Gallawa, 1976). The first basic difference is, of course, in the frequency range of interest. For example, Figure 2-1 shows a continuum of frequency from the microwave region, through the infrared, visable, and ultraviolet regions of the optical spectrum. The first subtle difference that the microwave engineer might note from this figure (relative to his conventional practice) is that frequency decreases from left to right (wavelength increases). This is rather common for optics, as wavelength is the dominantly used parameter rather than frequency. Note also that the quantity of photon energy (electron volts - eV) is indicated on the figure. This also is an important conceptual change in optical systems, as it reflects the fact that at these wavelengths we leave the concept of continuous power flow for that of quantum flow--the discrete amount of electromagnetic energy associated with the photon. Photon energy is a function of frequency, and is given by

$$E = h\nu, \tag{2-1}$$

where h is Planck's constant in watts $\cdot$ s^2 and ν is the frequency in Hz. Thus, energy is measured in watts $\cdot$ s (joules). We quickly come back to the concept of power in the optical domain however, by counting (in quantum steps) the number of photons received by a detector per second. Multiplication of this count with the photon energy yields power in watts. Thus, in reality, the optical detector is a photon counter--however, our consideration of the device in a communication system will be based on the concept of required received power to meet a certain operational requirement. This example serves to illustrate the meaning of some of the remarks in the opening paragraphs to this section.

The remainder of this section is devoted to presenting a summary of components and their associated parameters. The basic

parameters are included in each classification, and secondary considerations are briefly noted together with appropriate references where additional information can be obtained.

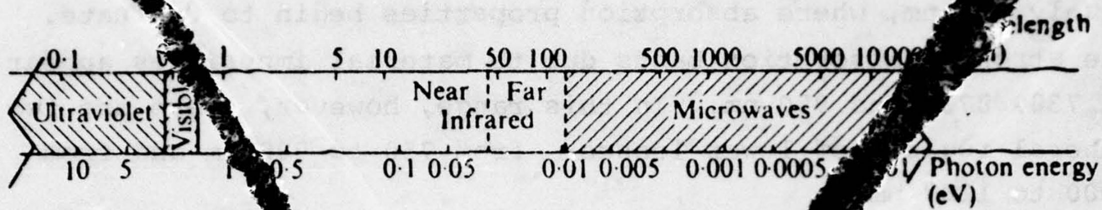


Figure 2-1. The electromagnetic spectrum.

The classification of components is as follows:

1. Optical driving sources (transmitters)
2. Optical detectors (receivers)
3. Optical fiber waveguides
4. Couplers and connectors

Before proceeding to the component section, we wish to insert at this point a brief discussion of parameters and terms that will be somewhat common to the component classifications above.

2-2. OPTICAL SYSTEM PARAMETERS

One of the first factors to be considered in the design of a microwave system is the choice of carrier frequency. For radiating systems, the frequency bands are first limited by allocation, usage, and secondly by assignment based on interference and geographical location considerations. For a completely closed waveguide system, however, these restrictions on frequency choice are considerably relaxed. In this instance, the dominant factor for choice is based primarily on loss factors. Such is the case in guided optical systems.

Figure 2-2 shows the typical attenuation characteristic of a high silica (glass) optical-fiber waveguide as a function of wavelength. Note that the baseline of this characteristic is roughly due to a scattering phenomenon since it closely follows

t[illegible] scattering attenuation curve (dashed line) in the figure. The scattering phenomenon will be discussed later. The general trend of this curve is downward (less attenuation) as the wavelength increases. This trend holds to wavelengths of approximately [illegible] nm where absorption properties begin to dominate. The strongest absorption bands due to material impurities appear at 730, 870, and [illegible] nm. In this range, however, there are two general regions of lower losses: from 750 to 900 [illegible] and from 1000 to 1100 nm.

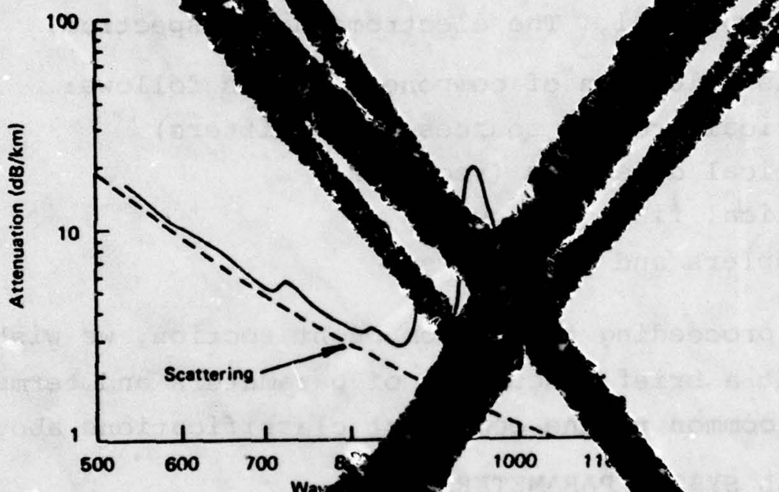
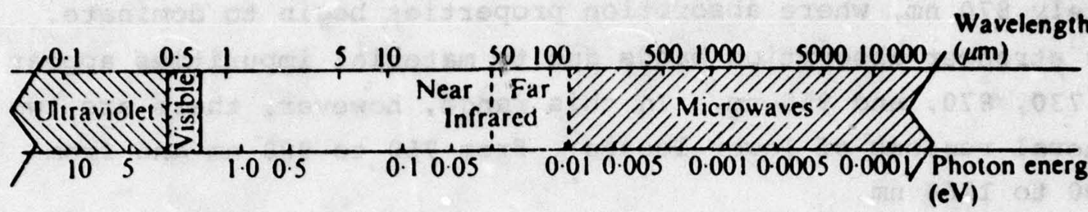


Figure 2-2. Attenuation characteristic of a low-loss high-silica optical fiber waveguide.

The lower band of wavelengths is found to be very compatible with currently available laser diodes (LD) and light emitting diodes (LED) made from AlGaAs. The higher wavelength band near 1000 nm is compatible with the emission line of Nd at [illegible] nm. The state of the art for driving sources essentially limits selection to the lower wavelength band between 750 and 900 nm. Therefore, most of the components and design procedures in this document are appropriate to this range. Fortunately, we find that the selection of detectors spans both of these lower-loss regions. For example, we will see that silicon detectors with good sensitivity are available up to about 1100 nm. With these

parameters are included in each classification, and secondary considerations are briefly noted together with appropriate references where additional information can be obtained.



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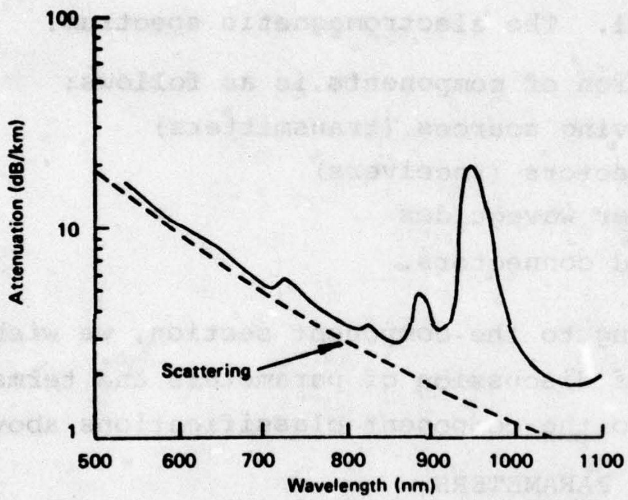
the scattering attenuation curve (dashed line) in the figure. The scattering phenomenon will be discussed later. The general trend of this curve is downward (less attenuation) as the wavelength increases. This trend holds to wavelengths of approximately 870 nm, where absorption properties begin to dominate. The stronger absorption bands due to material impurities appear at 730, 870, and 950 nm. In this range, however, there are two general regions of lower losses: from 750 to 900 nm and from 1000 to 1100 nm.



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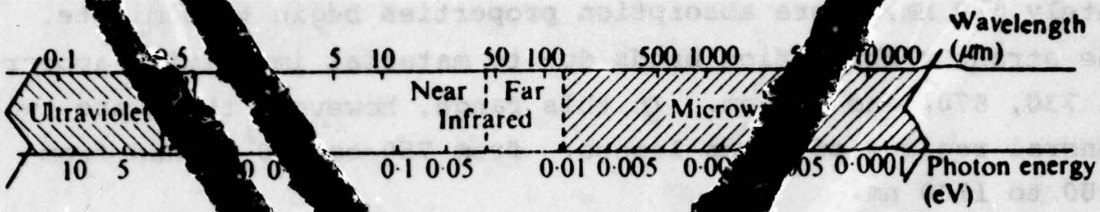

Figur[illegible]-1[illegible] The electroma[illegible]ic spectrum.

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observations, we have limited our range of wavelength, and identified the ranges that are commonly used relative to all three component classifications.

There is considerable development work being carried out currently in the higher wavelength region above 1000 nm. Interest in components at these wavelengths is prompted by the lower loss in the fibers. Note from Figure 2-2 that the loss can be decreased on the order of 1 to 2 dB/km at the longer wavelengths. However, there are offsetting penalties to be encountered, including the lower photon energy levels and increased response-time in detectors. In general, the materials technology is more difficult and less advanced (Kressel, 1977) at these longer wavelengths.

In addition to the above common framework for wavelength, we wish to establish the common set of terms and units that will be encountered in the specifications. Gallawa (1976) has summarized these, and we repeat his discussion and summary below. The most commonly encountered terms are given in Table 2-1. Complete definitions for each of these are also found in the Glossary.

Photometry is the science of specifying those aspects of the electromagnetic radiation which impact on vision. The communicator is not concerned with the response of the eye to watts of radiated power; instead, he is concerned only with the more definitive radiated power itself. The determination of radiated power is the task of <u>radiometry</u>; the task of <u>photometry</u> is to measure visual impact of a given radiated power. Photometry is an outgrowth of psychophysical experiments; radiometry is based on the need of the engineer to measure electrical power.

The distinction between photometry and radiometry did not become important until the advent of laser sources for communication in the visible part of the electromagnetic spectrum. There is a definitive relationship between photometric and radiometric terms and units. We will not be concerned with photometric terms except as they might be confused with radiometric terms. Table 2-1 illustrates the important differences between the sets.

Table 2-1. Terms and Units

Radiometric		Photometric	
Term	Unit	Term	Unit
radiant flux	watts (W)	luminous flux	lumen (lm)
radiant intensity (or intensity)	W/sr	luminous intensity	lm/sr
irradiance	W/m^2	illuminance	lm/m^2
radiance	$W/sr/m^2$	luminance or brightness	$lm/sr/m^2$ or c/m^2

In Table 2-1, the unit sr (steradian) is defined as a unit solid angle from the center of a sphere, one that encloses a surface equal to the square of the radius of the sphere. The total solid angle about a point is 4π steradians.

If a point source radiates photons in all directions, the radiant flux is the total energy per unit time (joules/s or watts) emitted in all directions. If the source is an extended source, a more important parameter is the radiance. The radiant intensity then depends on the area of the source. The expression for radiance depends on the angle of observation, but is independent of distance between source and observer. Irradiance is a measure of power incident on a surface. The units are watts per unit area (the area of the surface).

2-3. OPTICAL SOURCES

There are three fundamental types of optical-driving sources that are applicable to fiber-optic waveguides. These are:

1. Light emitting diodes (LED).
2. Semiconductor lasers (laser diodes - LD).
3. Non-semiconductor lasers.

Of these three, the current state-of-the-art limits the choice for practical sources to the first two. The nonsemiconductor (gas) laser, although the first type developed as a source of coherent light, is not presently well-suited as a driving source

for the microstructure of fiber waveguides. Types (including solid-state) for application in this technology are still in the fairly early stages of development. For this reason, our discussion here will be limited to consideration of LED and LD sources.

The nonsemiconductor (gas and solid-state) lasers will no doubt become important components in the future since they are capable of developing relatively high-drive levels. The disadvantages, however, include the requirement for high power supply voltages and external modulators. These devices can be pumped for their stimulated emission by the lower energy sources.

a. Light Emitting Diodes (LED)

Light emitting diodes (LED) are semiconductor devices that are constructed in much the same manner as other semiconductor components. Galium aluminum arsenide (GaAlAs) is the fundamental material used for these devices, even though other materials have been tried and are available. The spectral range is in the 700 to 910 nm wavelength band, which is seen to match closely one region of low attenuation in the fiber characteristic of Figure 2-2. The nominal wavelength applied is in the range 830 to 850 nm, in the attenuation null between absorption bands.

The basic semiconductor material is GaAs. In the development of these sources it was found that an alloy containing Al had some advantages. The most important from the user viewpoint is the effected change in emission wavelength as Al is substituted for Ga. The wavelength becomes shorter by a fixed increment for each percent of Al added, allowing flexibility in design, (tuning) (Bergh and Dean, 1972; Evtuhov and Yariv, 1975; Kressel et al., 1976). The advantages of these sources include their small size, ruggedness, capability of simple and direct modulation, and their spectral match with both fiber waveguides and silicon photodetectors.

The user should also be aware of a number of disadvantages associated with LED's. These are

1. broad angular spread of emission that causes less than ideal power coupling to fibers,

2. relatively low power output (< 3mw),
3. broad spectral emission which increases dispersion properties,
4. modulation rates limited to $\leq$ 100 MHz.

Second order features include low efficiencies, reliability questions, and temperature sensitivities. These factors must be considered by the designer in component selection. There are no general guidelines that can be delineated; these aspects must be checked with manufacurers' data and by inquiry. Some information on expected lifetime of some components is presented later in this section.

Structural features and manufacturing processes are beyond the scope of this document. However, these factors have played an important role in LED developments with respect to coupling efficiency. For this reason only, the reader should have a knowledge of the various geometries and the reasons behind them. Briefly, there are two classifications of emission for an LED; surface emitters and edge emitters. An explanation of the coupling problem can be simplified by considering the sketch of a surface emitter device for a flat-geometry in Figure 2-3. The light generating region is shown embedded in the device, and selected light ray-paths are depicted by arrows. Note that rays striking the refractive barrier (GaAs/air) at the surface at an angle other than normal, are either refracted away (Snell's law) from the normal external to the device, or reflected internally depending upon the angle of the ray at the surface. This is a simple introduction to the concept of an emission cone (solid angle) for these devices. It also forms the basis for a parameter which will be introduced later as the numerical aperture (NA) of the optical fiber.

It can be seen from Figure 2-3 that only those light rays within a defined emission cone can be emitted in the flat geometry. In addition, the emission rays are dispersed and those at large angles relative to the surface normal will be difficult to couple into the optical waveguide. It is clear that a structural

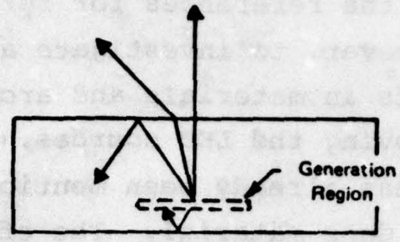


Figure 2-3. A surface emitting source with flat geometry.

arrangement that will either increase the emission cone and/or change the direction of the rays striking the interface will increase total emission (radiant intensity). Two such structures for the surface emitter class of LED's are depicted in Figure 2-4. These are known as shaped-geometry sources. The hemispherical type is seen to increase the number of emitted rays by providing a normal angle with the surface for any source ray within the hemisphere. The truncated spherical emitter accomplishes this result also, but adds some coherence to the direction of emitted rays and a corresponding increase in radiant intensity.

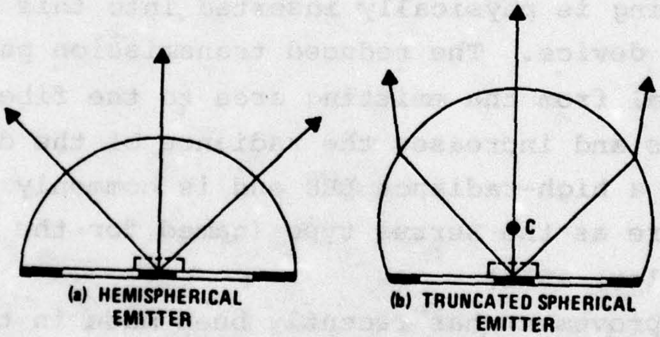


Figure 2-4. Surface emitting sources using shaped geometries (Dierschke, 1975).

The improvement in efficiency (external to internal radiant intensity) of structures such as those in Figure 2-4 can be calculated theoretically and compared with measurements on actual devices. Work of this nature has been reported by Dierschke (1975). The theoretical improvements have not been met in commercial practice, primarily due to internal absorption and Fresnel reflections at surfaces. These matters are beyond our

scope and are left to the references for further consideration. It is informative, however, to investigate at least the background of a few aspects in materials and architecture that have had an impact on improving the LED sources.

One development has already been mentioned; it is the addition of Al to the GaAs material. The effects of this material change are summarized in Figure 2-5 where the transmission and luminescent properties of the two materials are shown. The addition of Al (15% in this example) has extended the transmission band to higher energy levels (lower wavelengths) compared to the GaAs material. Note that the GaAs generation spectrum is both distorted and attenuated in its emission spectrum by the pure material transmission band. The alloy material is more transparent to the total generation spectrum, and thus improves the emission intensity (Dierschke, 1975).

An example of LED architectural improvement is illustrated in Figure 2-6. An "etched well" is created in the n-type GaAs material over the primary light-emitting area, and the optical fiber for coupling is physically inserted into this well and expoxied to the device. The reduced transmission path through the GaAs material from the emitting area to the fiber greatly reduces the loss and increases the radiance of the device. This structure forms a high-radiance LED and is commonly referred to in the literature as the Burrus type (named for the developer) (Burrus and Miller, 1971).

Another improvement has recently been made in the Burrus structure. An array of microlenses are fabricated in the bottom of the etched well to collect the light from the junction more efficiently. This complicates the manufacturing process, but it has been shown that up to twice the power can be coupled to the fiber using this technique (King and Springthrope, 1975). One manufacturer has produced a device using a single (glass) microlens deposited in the bottom of the well. The objective of the variations in structure and material in the surface emitter is to increase the overall radiance ($W/cm^2 \cdot sr$) of the device. This

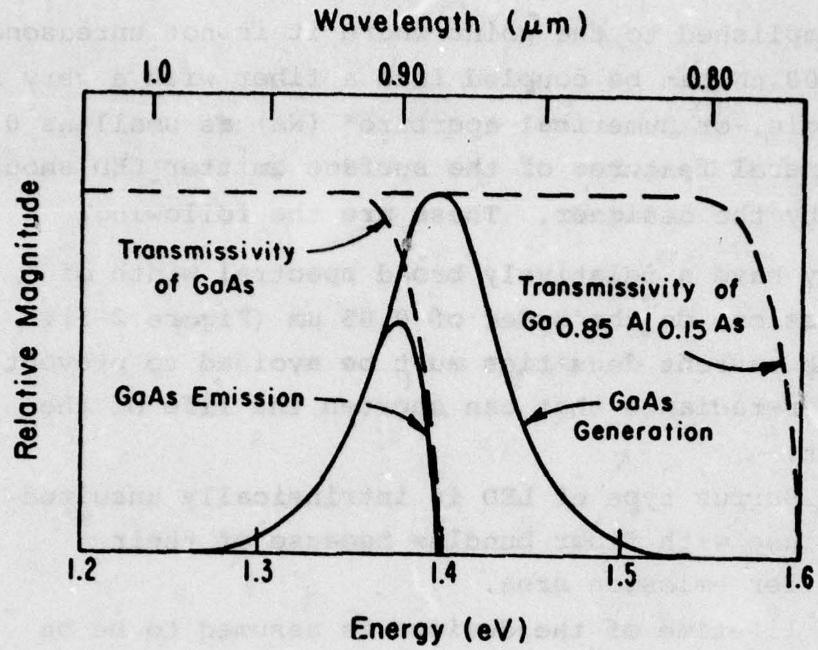


Figure 2-5. Transmission and luminescent properties of GaAs and GaAlAs materials.

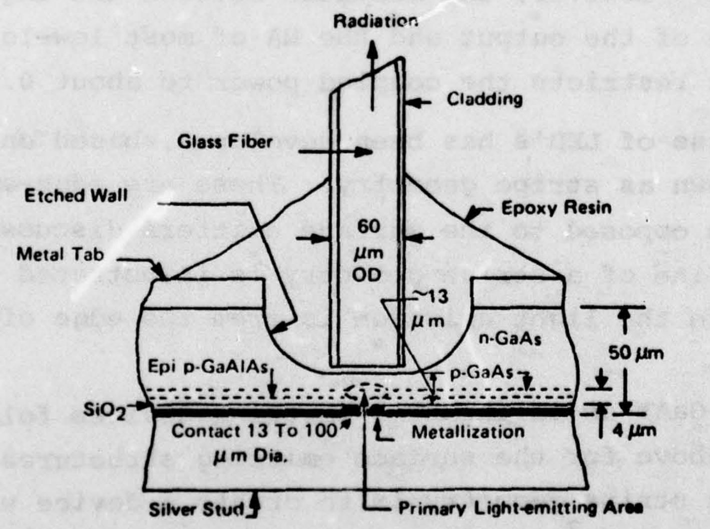


Figure 2-6. Illustration of a high-radiance (Burrus type) LED (Electronic Design, Feb. 17, 1972, p. 29).

has been accomplished to the point where it is not unreasonable that 300 to 500 μW can be coupled into a fiber with a very small acceptance angle, or numerical aperture* (NA) as small as 0.2.

A few general features of the surface emitter LED should be kept in mind by the designer. These are the following:

1. They have a relatively broad spectral width of emission; on the order of 0.05 μm (Figure 2-5).
2. High current densities must be avoided to prevent super-radiance that can shorten the life of the unit.
3. The Burrus type of LED is intrinsically unsuited for use with fiber bundles because of their smaller emission area.
4. The lifetime of the devices is assumed to be on the order of 25,000 hours (mean time between failure--MTBF). However, most manufacturers to date are reluctant to specify the MTBF.
5. Some devices are producing up to 1 mW in power output. However, the mismatch between the angular spread of the output and the NA of most low-loss fibers restricts the coupled power to about 0.1 mW.

Another class of LED's has been developed, based on an architecture known as stripe geometry. These are edge-emitter type devices, as opposed to the surface emitters discussed above. The outline of a stripe geometry is illustrated in Figure 2-7, where the light emission is from the edge of the structure.

The use of GaAs as in the edge-emitting devices follows from the discussion above for the surface emitting structures. The objective of the stripe geometry is to create a device with high radiant intensity (W/cm^2) as opposed to overall radiance. In these devices, the source area is generally smaller than the associated fiber area, and thus radiant intensity is the appropriate parameter for optimization.

*Numerical aperture is defined in Section 2-5 c.

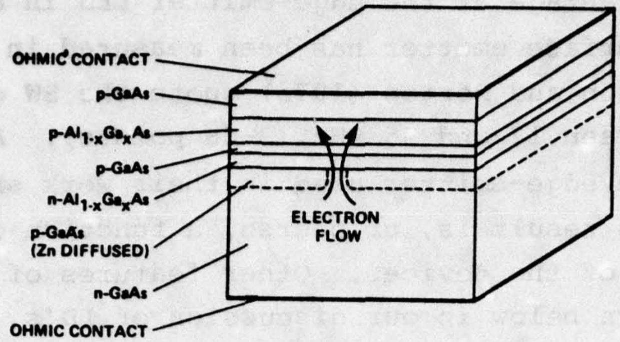


Figure 2-7. Illustration of an edge-emitting source with stripe geometry (Rawson & Norton, 1975).

The primary advantage to the edge-emitter LED is its good match in size of the emission beam to the diameter of a single-fiber multimode waveguide. The Burrus-type LED discussed above emits much more total light than the stripe-geometry device, but over a larger area. In general, the surface emitter LED will underfill the small single fiber. Rawson and Norton (1975) have shown the concentrated emission area of this LED device compared with the core diameter of an optical fiber through infrared photography. A photograph from this reference is shown in Figure 2-8, where a 75-nm core diameter is superimposed on the photograph of the edge emission. These authors have also demonstrated the application of this LED in a digital link 0.5 km in length, with data rates in excess of 150 Mb/s.

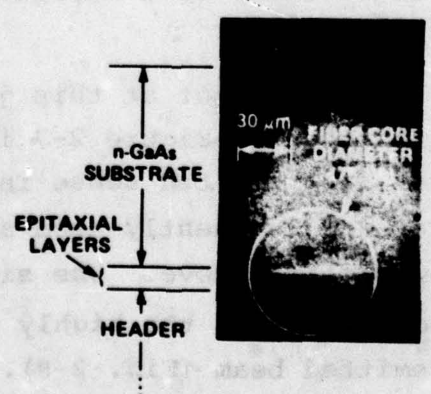


Figure 2-8. An infrared photograph of the emission from a striped substrate device (Rawson and Norton, 1975).

Another advantage of the edge-emitter LED in comparison with a Burrus-type surface emitter has been measured in terms of bandwith (BW). Rawson and Norton (1975) quote the BW of Burrus-type LED's to be between 17 and 35 MHz (3-dB points). A measurement performed on the edge-emitter used in their work showed a 3 dB BW of 90 MHz. This result is, of course, a function of the on-off switching speed of the devices. Other features of this edge-emitter are shown below in our discussion of LD's, or the semiconductor laser source (sec. 2-3 c.).

Edge-emitting LED's are also produced for application in fiber-bundle technology. A typical structure is a reflector-type as illustrated in Figure 2-9. The edge-emitter source is imbedded in a structure containing an elliptical reflecting surface formed in the cathode material. The focusing effect of the reflector on the edge-emitting light rays is illustrated in the figure.

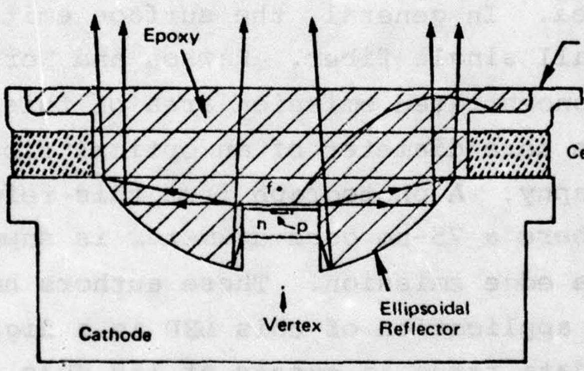


Figure 2-9. Illustration of a reflector-type edge emitter.

It perhaps should be pointed out at this juncture that the stripe-geometry device sketched in Figure 2-7 is a laser structure. We will discuss this fact in a limited sense in the next section. However, these structures are frequently used as high-brightness LED's, with the advantages cited above. One significant disadvantage of the edge-emission device is the highly asymmetric shape of the source area and emitted beam (Fig. 2-8). It is not geometrically well-matched to a circular fiber cross-section. However, it has been pointed out that the radiant density is

high, and concentrated in narrow widths commensurate with the optical-fiber dimension. Depending upon the desired output characteristic, the latter property may be more important for design considerations than the geometry mismatch.

Bandwidths for either of the two LED types can be extended by providing nonlinear drive circuits. Theoretically, the BW can be extended by an order of magnitude in this manner, but due to other adverse effects, a practical improvement is limited to a factor of about three. BW characteristics (or the speed of devices) can be controlled to a degree also by methods of doping in the manufacturing process.

A brief summary of characteristics for typical LED's is presented in Table 2-2. The price information is based on manufacturers' data in 1976 (A. D. Little, Inc., 1976). The conglomerate of figures noted under the power column of this table illustrates the lack of standards, even in stating output values in common terms.

For system applications involving any form of analog modulation techniques, another property of the driving source to be considered is the linearity of the device. LED sources are inherently nonlinear in their characteristic of output light intensity as a function of drive current. This is illustrated for a representative LED in Figure 2-10 (Wittke, 1975). The drop in the characteristic at high current values under dc drive conditions is caused by heating effects. The distortion products for a representative LED source have been measured (Straus and Szentesi, 1977) at a fundamental frequency (ω) of 1 kHz. Results are given in Figure 2-11. Similar results were obtained up to 5 MHz. At higher frequencies, the linearity improve 2 to 3 dB as the bias current increases. Additional measurements were made by Ozeki and Hara (1976); their data show that in some cases third order products are on the order of 60 to 65 dB below the fundamental. These values are not considered to be low enough for the best quality of a color television signal in an analog system. Some techniques for improving linearity are discussed in Chapter 5.

Table 2-2.

CHARACTERISTICS OF TYPICAL LEDs

Device	Manufacturer	Drive Current (mA)	Emission Wavelength (μm)	Spectral Width (μm)	Power	Price ($)
40-3-10-2		150	0.84	0.45	22[a]	475
40-3-15-2	Bell-Northern Research	150	0.84	0.045	33[a]	475
40-3-30-2		150	0.84	0.040	66[a]	475
IRE150	Laser Diode Laboratories	100	0.82	0.035	1.5[b]	45
TL-24C	Meret	50	0.905	–	1[b]	19
TL-36C		300	0.905	–	12[b]	25
ME60	Monsanto	50	0.9	0.04	0.4[b]	1.04
GAL100		50	1.063	0.055	0.5[b,c]	600
HR952	Plessey	300	0.9	0.03	10[a]	150
HR953		300	0.9	0.03	20[a]	190
HR954		300	0.9	0.03	35[a]	300
SG1009		100	0.94	–	3.5[b]	1.75
C30116	RCA	50	1.06	–	0.04[b]	250.
C30119		200	0.85	0.05	0.5[b]	90.
C30123		200	0.83	0.05	1[b]	75.
SE2450-2	Spectronics	50	0.93	0.036	0.36[a]	1.87
SPX2231		100	0.907	0.024	2[a]	40

[a]Radiance in W/cm^2·sr

[b]Power in mW

[c]Pulsed

(Source: A.D. Little, 1976)

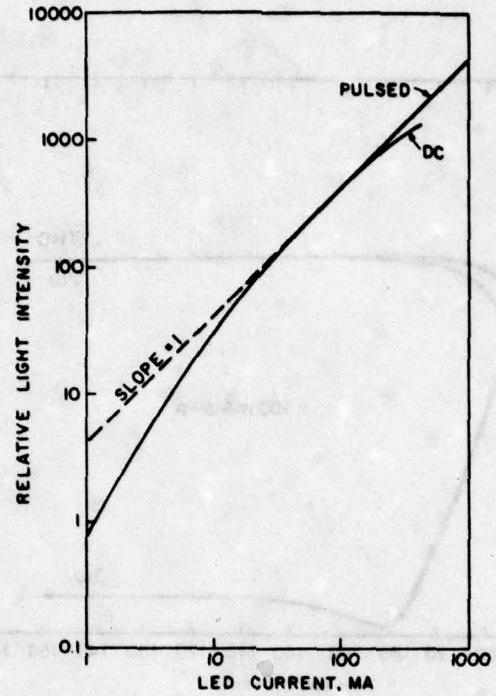


Figure 2-10. Nonlinear response of a representative LED. (Wittke, 1975).

Noise is not a serious problem in LED sources. It is limited to small amounts of shot noise and random noise inversely proportional to the spectral width of the device. In comparison with other sources of system noise, these contributions are generally negligible.

b. Summary of LED's

The primary application features for LED sources are summarized in the following:

1. Common factors.

   - Both types (surface and edge emitters) can be used in digital applications at low to medium data rates.

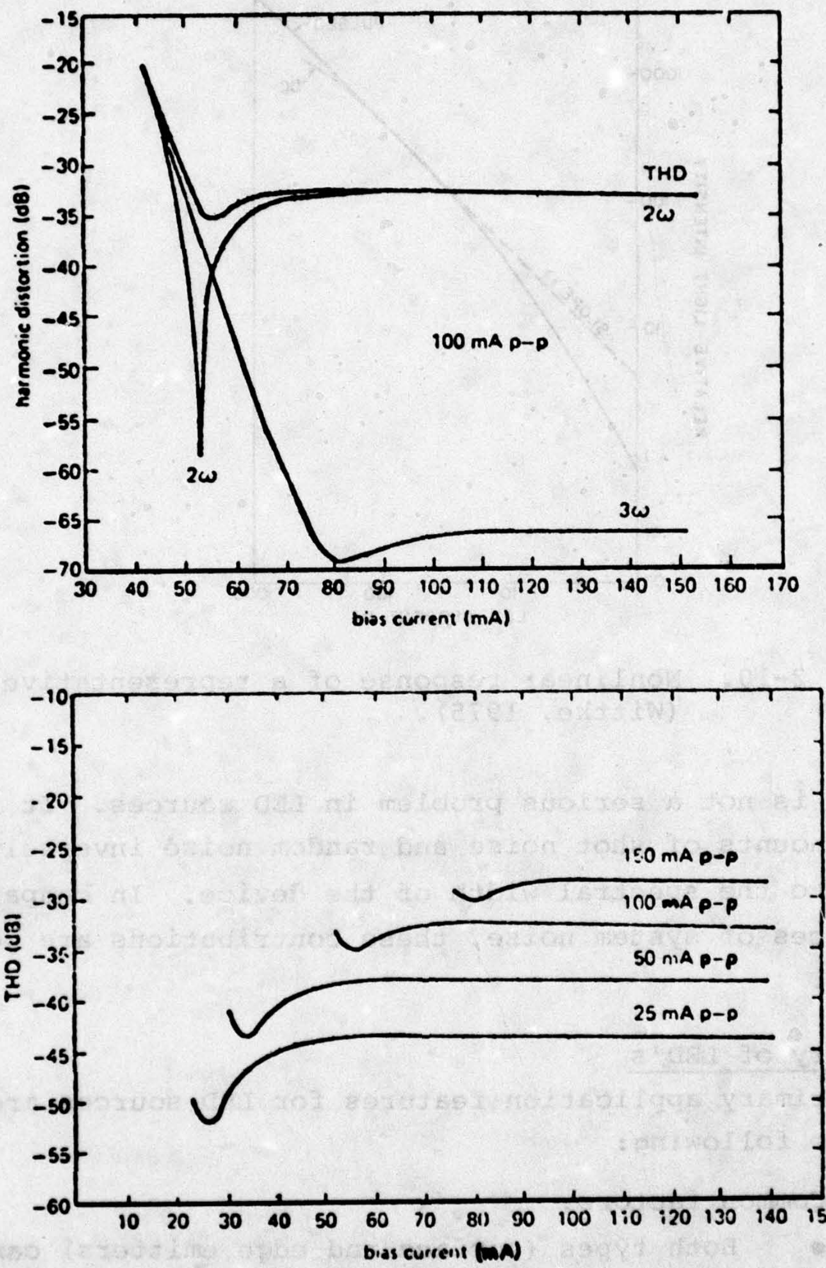


Figure 2-11. Harmonic distortion of a typical Ge doped double heterostructure LED. (a) total harmonic distortion; (b) harmonic components (from Straus & Szentesi, 1977).

- They are not optimum for use in analog systems requiring good linearity.
- Simplicity and ruggedness are attractive features.
- Both structures appear to have equivalent MTBF.
- Power coupling to small aperture fibers is quite low (25 to 100 μW).
- For fibers of NA > 0.3 and the fiber bundles, the LED is a viable source for length - BW products to about 20 to 30 km - MHz.
- Choice between types will be based on specific application needs, compatibility, price and availability.

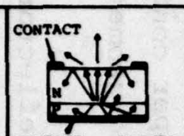
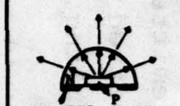
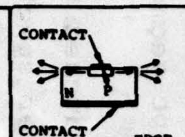
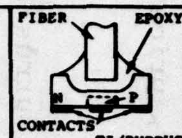
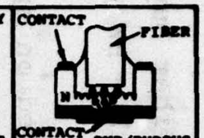
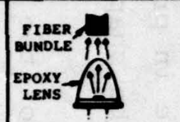
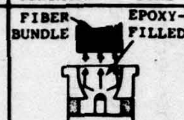
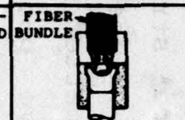
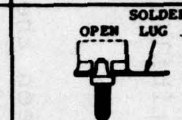
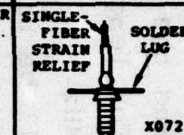
2. Single Fiber Applications.
   - Component choice is between the Burrus type and the double heterostructure* stripe geometries--both have equivalent radiance values.
   - Burrus-type sources are better matched to fiber acceptance cones, but have poorer spectral width and BW properties than the edge emitters.
   - Lens modification of the edge emitted beam may be advantageous for small fiber coupling.
3. Fiber Bundle Application.
   - Both types are applicable in proper configuration.
   - Surface emitters should be shaped-geometry sources (Fig. 2-4).
   - Edge emitters should be of the reflector type (Fig. 2-9).

A useful tabular summary of the LED sources discussed in this section is presented in Table 2-3 (from Casper, 1975).

*In this discussion, we have attempted to avoid structure terminology. However, the double heterostructure reference is quite common in the literature, and is indicated with the acronym DH.

Table 2-3.

Typical Characteristics of LED Sources

LED CHIP TYPES	PLANAR	DOME	EDGE	TI/BURRUS	BMR/BURRUS
					
PACKAGING	 EPOXY TO-18	 PARABOLIC REFLECTOR	 ELIPSOIDAL REFLECTOR	 TO-5 STUD	 X072 STUD
RADIATING SPOT DIAMETER	2.7 mm (1 cm FROM LENS)	2 mm	1.1 mm	0.075 mm	0.075 mm
ON-AXIS RADIANT INTENSITY (W/Sr) / ON-AXIS RADIANCE ($W/SR-Cm^2$) (100 ma)	10 mW/Sr / 0.36 $mW/Sr-Cm^2$	7 mW/Sr / 0.35 $W/Sr-Cm^2$	4.7 mW/Sr ± / 0.467 $W/Sr-Cm^2$ ±	0.27 mW/Sr * / 6 $W/Sr-Cm^2$	2.7 mW/Sr / 60 $W/Sr-Cm^2$
TOTAL RADIATED POWER (100 ma) / EMISSION 1/2 POWER ANGLE	1.0 mW / $\approx \pm 12^{\circ}$	3 mW / $\pm 12^{\circ}$	2 mW / $\pm 15^{\circ}$	0.8 mW * / $\pm 45^{\circ}$	5 mW / $\pm 45^{\circ}$
0.707 BANDWIDTH / SPEED	35 MHz / 10 ns	23 MHz / 15 ns	23 MHz / 15 ns	23 MHz * / 15 ns	25 MHz / 14 ns
COUPLED POWER INTO SINGLE, LOW-LOSS FIBER (CORNING)	$< 1 \mu W$	$\approx 1 \mu W$ (AT "HOTSPOT")	$\approx 3 \mu W$ (AT "HOTSPOT")	$20 \mu W$ *	$125 \mu W$
COUPLED POWER INTO 0.045-INCH CONVENTIONAL BUNDLE	$200 \mu W$	$600 \mu W$	$1000 \mu W$	UNSUITABLE	UNSUITABLE

* OBJECTIVE PERFORMANCE FIGURES
± AVERAGED OVER THE 1.1 mm APERTURE

(Source: Casper, 1975)

c. Laser Diode Sources (LD)

This class of optical sources is limited (as noted previously) to the semiconductor injection laser (IL). Solid state or gas lasers are not considered for application to fiber-optic systems at this time, even though commercial developments are known to exist. The semiconductor class is generally labelled as laser diodes (LD). However, the nomenclature of "DH" laser is also common.

The GaAlAs material dominates the semiconductor laser field as it does in the LED's as noted above. Basically the material is in the injection laser classification since it is used as a current pumped source, even for LED operation. In this sense, any of these devices have a region in which lasing can be induced. This characteristic is depicted in Figure 2-12, where the lasing region is shown beyond a threshold value of drive current. The rapid increase in output power is inherent to the lasing action.

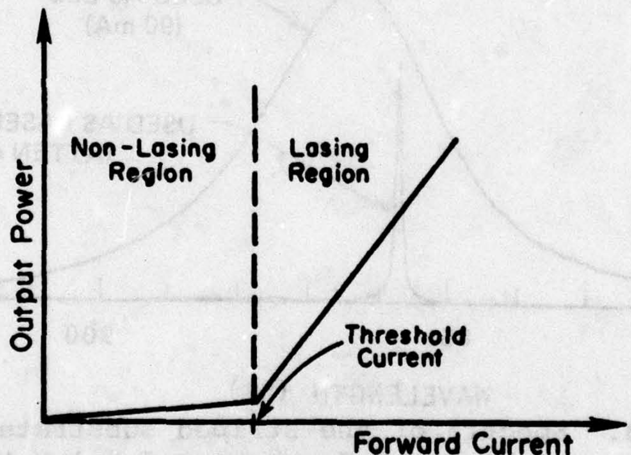


Figure 2-12. Power-current relationship for a diode source.

The major advantage and the disadvantage of the LD source are each seen in Figure 2-12. Obviously, the increased output power is the biggest advantage compared to the LED source. However, the penalty paid is embodied in the high drive current required for the LD, which means high current densities in the emission region. Since the semiconductor material is common to the LED's

and LD's of interest, the spectral range of operation is essentially the same for both devices. Therefore, the general comments on spectral match with fiber attenuation properties etc., which were made in the previous section on LED's, also apply to the LD's.

An example of a particular edge-emitting source introduced in Figure 2-7 is convenient for illustrating fundamental differences and similarities between LED and LD sources. The operation of this particular device is described in both modes by Rawson and Norton (1975). For example, the radiant spectrum of the device is shown in Figure 2-13 where it is used both as an LED and as a LD. Note the dramatic change in spectral width of emission above threshold (lasing). In addition, the response for the LD operation is attenuated by a factor of 43 in the relative magnitudes shown. The difference in forward bias current is indicated in the figure.

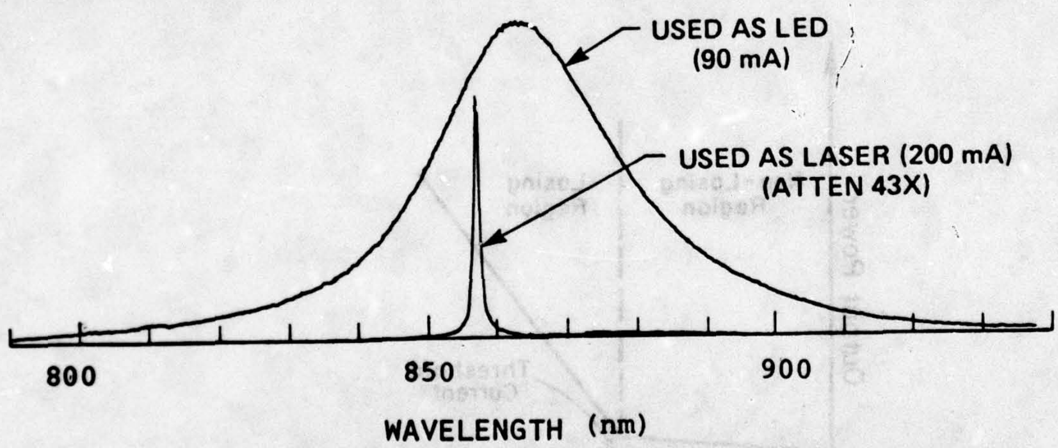


Figure 2-13. Spectra of the striped substrate source of Figure 2-7, above and below threshold.

Together with the spectral measurements, the radiance of the device as a function of radiation angle was measured, by the above authors, and the results are shown in Figure 2-14. The characteristic in the lasing region is shown for the plane parallel to the junction plane, and also perpendicular to the junction plane. These responses show graphically the asymmetric radiance band shown pictorially in Figure 2-8 for the edge-emitting unit.

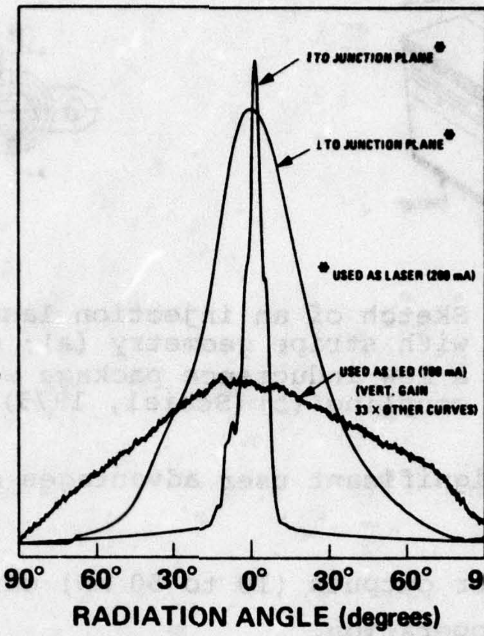
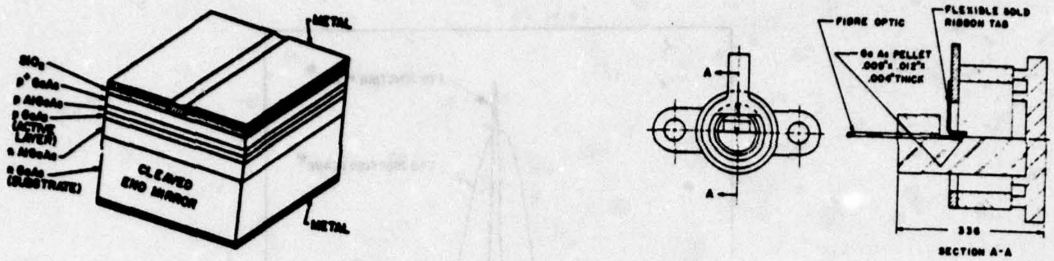


Figure 2-14. Angular radiation distribution of the edge-emitting source of Figure 2-7.

The *significant* developments in these devices include the advantages brought about by the addition of Al to the GaAs material. Also the DH structure reduces radiation losses in the active region. Other improvements have been made by providing optical feedback to form a laser cavity by controlling reflectivity at various facets within a single crystalline chip. The facets are coated with protective oxide layers which serve to reduce Fresnel reflection losses, and electrically isolate the junction from a reflecting metal layer used on the nonemitting face of the unit. The basic structure of the DH type LD and a typical package are illustrated in Figure 2-15 (Schiel, 1975). The fiber for coupling is mounted in a V-groove opposite the emitting (edge) facet of the chip in the package shown.



(a) (b)

Figure 2-15. Sketch of an injection laser (LD) source with stripe geometry (a); cross section of a low inductance package with fiber coupling (b) (Schiel, 1975).

Some of the significant user advantages of the LD can be cited as:

1. High power outputs (10 to 50 mW) can be obtained with cw operation.
2. Beam spread is ~15° in the junction plane.
3. Coupling losses to a multimode fiber are on the order of 3 to 4 dB lower than for a similar LED.
4. Easily modulated by change in drive current.
5. Recombination times are shorter, permitting faster modulation rates (exceeding 1 GHz).
6. Ideally suited to pulse modulation forms (PCM, PPM, PFM).
7. Drive pulses can be applied either at zero level, or superimposed on a pre-bias current near threshold.
8. Spectral width of emission is considerably smaller than for LED's, and thus dispersion effects over long-distance fibers are greatly reduced.

A brief summary of characteristics of some typical LD's is presented in Table 2-4. The price information is based on that available in 1976, and is included for comparative purposes only.

Modulation of the LD's is generally accomplished by controlling the drive current to the device, as in the case for LED's. However, for digital modulation different bias arrangements are used. Without bias, the modulation signal is combined with the

Table 2-4. Characteristics of Typical Lasers

Device	Manufacturer	Threshold Current (mA)	Power (mW)	Emission Wavelength (μm)	Price ($)
LCW5	Laser Diode	200	7	0.85	250
LCW10	Laboratories	200	14	0.85	350
C30127	RCA	250	5	0.82	350
C30130		250	6	0.82	375

Source: A.D. Little, 1976.

current drive source below lasing threshold, and each pulse input drives the source into the lasing region. The technique results in a time delay, and the noise associated with the threshold transition (see below) is inherent. A pre-bias current can be used to hold the quiescent point just below the lasing threshold, and the modulating signal is superimposed on the fixed bias. This improves the speed of response eliminating much of the time delay, but does not remove the noise associated with threshold transition. The device may also be operated continuously above threshold with a proper bias level, and the modulating signal superimposed on the drive current. The latter method is obviously required for analog modulation in which the bias must be high enough to prevent clipping on the negative-going limits of the modulating signal. The fixed bias above threshold eliminates the transition noise of the LD, but the steady-state emission in this mode will cause photon-induced noise in the photo-detector at the receiver.*

Noise in LD's is found to be a function of the drive current. As noted above, there is an increase in noise output near the threshold transition. As the drive current increases, the noise subsides, until at high levels more noise is induced by extraneous lasing modes that are established. This latter noise is generated at very high frequencies, usually above about 700 MHz. It can be controlled by limiting the BW of drive circuits and with various forms of feedback (either optical or electronic). The unfortunate feature of the high-frequency noise is that it appears to be

*See also the notes on lasers in Chapter 3.

greater in devices with the highest material purity which improves reliability (MTBF).

The linearity property of LD's is not significantly different from that for LED's. However, some units display severe kinks in their light-output-vs.-drive-current characteristic, which compound the nonlinearity problem. Straus and Szentesi (1977) have measured the distortion products for a typical double heterostructure injection laser. Their results are shown in Figure 2-16. It can be seen in comparison with Figure 2-11 that the nonlinearity problem is comparable in both sources.

As in the case of LED's, the reliability of LD sources is not well-known or documented. There is currently a disparate gap between the expected MTBF figures that are quoted in the literature, and those that manufacturers are willing to specify or warrant. This fact encumbers the designer in making engineering decisions. Much more work is required on these devices before reliable information is available relative to life expectancy, and operational variations that can be used to extend the life. A general guide to MTBF for a number of LD's is given in Table 2-5 (A.D. Little, Inc., 1976). The data presented were collected from professional and trade journals as well as manufacturer's literature. The characteristics should be viewed as representative of typically achieved results and not as the latest or best possible.

One manufacturer has recently announced in the press an LD expected life of 1 million hours (>100 years), based on aging tests conducted at high temperatures (TV Digest, 1977). Another manufacturer has announded plans to deliver units of 100,000 hours life expectancy in the near future.

d. Summary of LD Sources.

The specific details of selecting an appropriate driving source for an optical-fiber system will depend on system requirements. These considerations are presented in Chapter 6 of this document. Since we are not considering, at this time, any laser source outside of the semiconductor class, the basic choice of

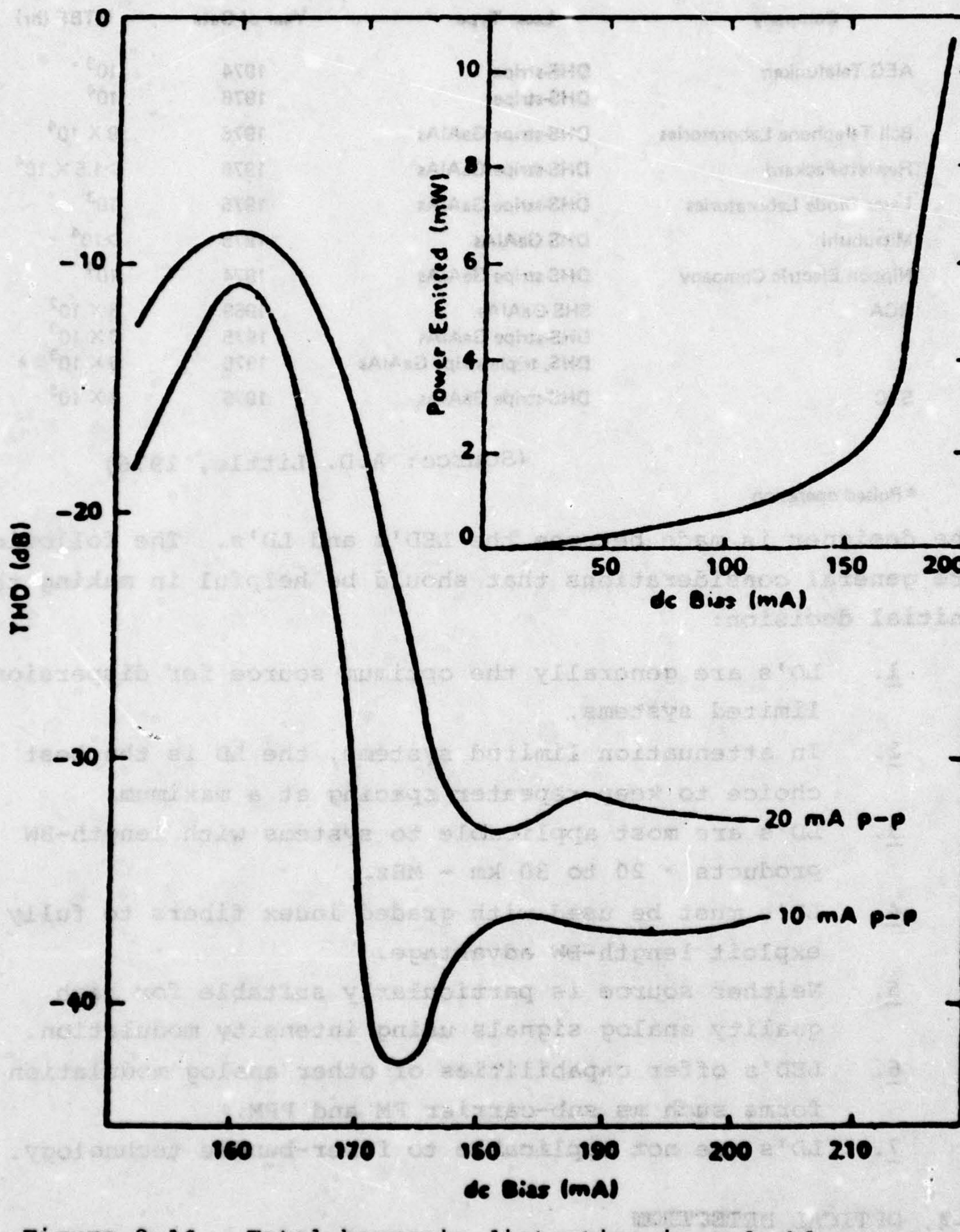


Figure 2-16. Total harmonic distortion in a double heterostructure injection laser. The insert shows the power emitted from one facet of the laser as a function of dc bias (from Straus & Szentesi, 1977).

Table 2-5. MTBF Semiconductor Lasers

Company	Laser Type	Year of Data	MTBF (hr)
AEG Telefunken	DHS-stripe	1974	10^3
	DHS-stripe	1976	10^4
Bell Telephone Laboratories	DHS-stripe GaAlAs	1976	9×10^4
Hewlett-Packard	DHS-stripe GaAlAs	1976	$>1.5 \times 10^4$
Laser Diode Laboratories	DHS-stripe GaAlAs	1975	10^3
Mitsubishi	DHS GaAlAs	1975	$>10^4$
Nippon Electric Company	DHS-stripe GaAlAs	1974	10^4
RCA	SHS GaAlAs	1969	3×10^2
	DHS-stripe GaAlAs	1975	3×10^3
	DHS, triple stripe GaAlAs	1976	6×10^3 *
STC	DHS-stripe GaAlAs	1975	6×10^3

(Source: A.D. Little, 1976)

* Pulsed operation

the designer is made between the LED's and LD's. The following are general considerations that should be helpful in making the initial decision:

1. LD's are generally the optimum source for dispersion limited systems.
2. In attenuation limited systems, the LD is the best choice to keep repeater spacing at a maximum.
3. LD's are most applicable to systems with length-BW products > 20 to 30 km - MHz.
4. LD's must be used with graded index fibers to fully exploit length-BW advantage.
5. Neither source is particularly suitable for high quality analog signals using intensity modulation.
6. LED's offer capabilities of other analog modulation forms such as sub-carrier FM and PPM.
7. LD's are not applicable to fiber-bundle technology.

2-4. OPTICAL DETECTION

Unlike the other components necessary to an optical-fiber communications system, optical detectors (or photodetectors) have been available and applied for some time. Consequently, more is known about the operation and life expectancy of these com-

ponents. The function of the photodetector is to convert the received optical power into an appropriate electrical signal as depicted in Figure 2-17 (Gallawa, 1976).

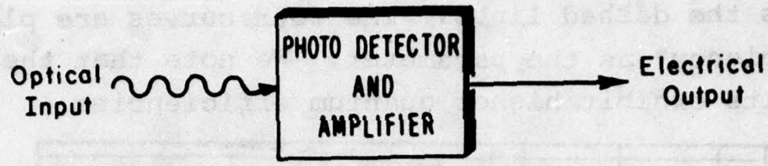


Figure 2-17. Illustration of converting optical power to an electrical signal.

The photodetector provides an output current which is proportional to the time average of the square of the electric field over the photosensitive surface area and over the response time. Clearly, the detector is an integrating device, the integration time being long compared to the optical period, $1/\nu$, and short compared to the shortest modulation period. The detector response time will, therefore, be an important parameter. If the photosensitive surface area of the detector is large, the output is averaged accordingly; this will be a disadvantage if the illumination varies over the surface.

The photocurrent of the detector is proportional to the average of the carrier power (p_c), over the period of the carrier and is given by

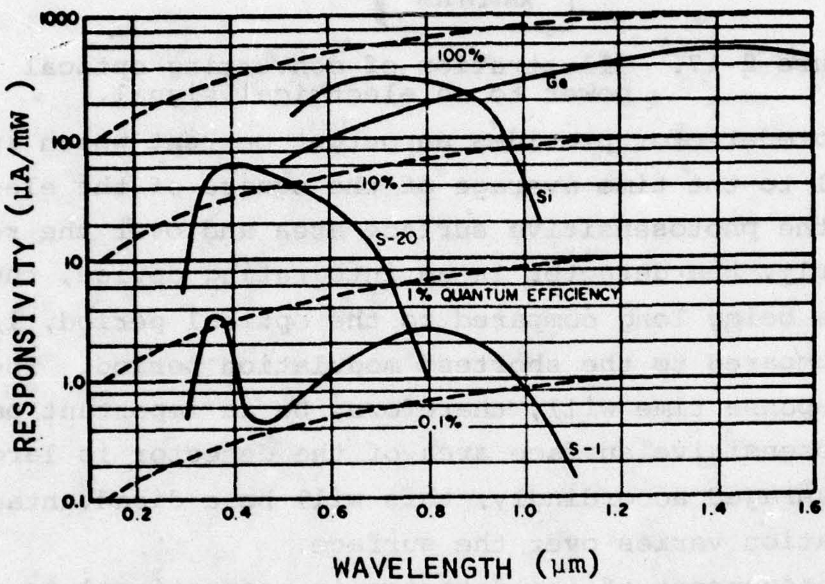
$$I = \eta q p_c / h\nu, \tag{2-2}$$

where $h\nu$ is recognized from Equation (2-1) as the photon energy, and η and q are factors of proportionality. Responsivity is an important parameter of detectors, and from Equation (2-2) is defined as

$$R = \eta q / h\nu, \tag{2-3}$$

which is seen to be the ratio of output current to the incident optical power (amps/watt). This characteristic is linear if the value of η is constant. However, η varies with wavelength and material so that the responsivity of different devices is not linear and varies as a function of wavelength. Figure 2-18 shows this parameter plotted for four devices. The two higher curves

are for Ge and Si semiconductors, respectively; the lower curves are for two photocathode materials. The material codes are noted in the figure. For comparative purposes, the curves for responsivity where η is assumed constant with wavelength are shown in the figure as the dashed lines. The four curves are plotted with quantum efficiency* as the parameter. We note that the semiconductor units exhibit higher quantum efficiencies.



S − 1 = AgOCs S − 20 = Na_2KSbCs

Figure 2-18. Responsivity of optical detectors.

The sharp change in responsivity is assumed to be a result of insufficient photon energy (some critical value) to excite electron activity. Note that the Ge semiconductor exhibits the broadest range with wavelength, and is higher in responsivity than the other devices at wavelengths >0.9 μm. However, in the range of wavelength of most interest currently (0.82 to 0.85 μm), the Si semiconductor is the highest. It falls off quite rapidly above $\lambda = 0.9$ μm.

Next to responsivity, the noise characteristics of a photodetector are most important. Just as the noise characteristics of a radio system are usually dominated by the noise figure of

*Quantum efficiency is defined in the glossary section.

the receiver, the noise figure of merit for the photodetector will usually dominate in the optical system. Gallawa (1976) has presented a comprehensive discussion of optical noise sources, noise generation, and signal-to-noise ratios (SNR). We will avoid any duplication of this work here but will draw from it and present the most important results in the course of the discussions below.

An important aspect of optical noise that will be unusual to the microwave engineer should be emphazised. This is shown in the characteristics plotted in Figure 2-19. The noise spectral density commonly known as kT or thermal noise is shown in the figure as a function of frequency, and is seen to be quite constant up to frequencies near 10^{12} Hz. Above this frequency, the thermal noise density begins to decline and drops off rapidly above 10^{13} Hz. Thus, at microwave and higher radio frequencies, the concept of white noise (uniform or constant density) is common. Also plotted in Figure 2-19 is the characteristic for quantum noise shown by the curve labeled $h\nu$. This noise dominates in the optical frequency range, and increases with frequency. This noise density is sometimes referred to as blue noise. The composite noise density curve for standard earth temperature (290° K) is shown by the solid line curve ($\psi(\nu)$) in the figure. Since the systems of interest here will operate at frequencies above 10^{14} Hz, the quantum noise will dominate and thermal noise will be negligible. However, this should not be construed to mean that the optical system designer has emerged from the impact of thermal noise; we must deal with it again when we consider the opto-electric interface in the receiver system. The remark here is limited to the photo-detector and does not apply to its associated amplifier or other circuitry. A composite view of the noise sources to be considered in the optical receiving system is shown in block diagram form in Figure 2-20.

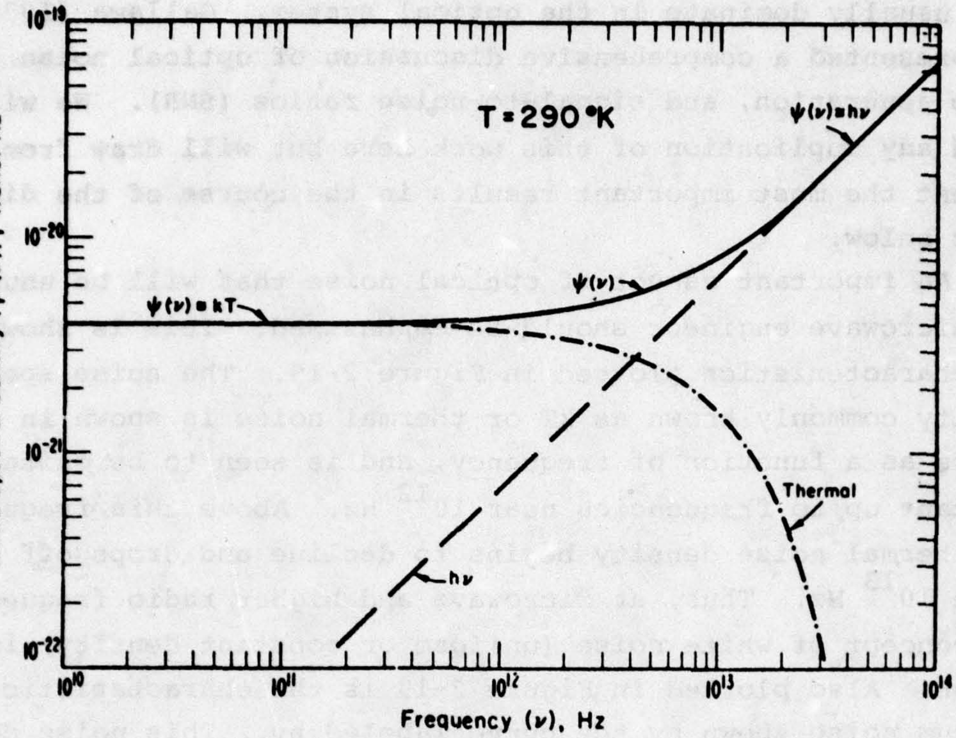


Figure 2-19. Noise spectral density as a function of frequency.

We will return to the discussion of noise and SNR characteristics later in this section. At this time we shall only introduce a term that has become a figure of merit for photodetectors, as it will be used in component discussions and comparisons. The term is noise equivalent power (NEP), which is defined as the rms value of optical power required to produce a unity SNR at the output of a detecting device. The concept of equivalent power is seen from the definition, and the utility of the ratio as a figure of merit can be noted in the fact that all devices can be compared on the basis of a single performance-oriented factor.

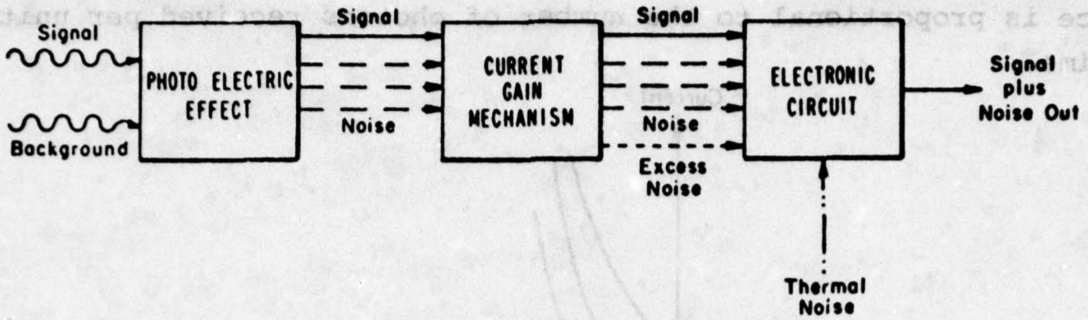


Figure 2-20. Block diagram depicting the sources of system noise.

a. Classification of Photodetectors

There are a number of different types of photodetectors, ranging from large photo-emissive and photo-multiplier vacuum tubes to solid-state and semiconductor units. In our discussion here, we will be concerned with the latter devices since they are the only currently appropriate units for fiber-optic systems. Gallawa (1976) discusses a number of different types of solid-state photodetectors and distinguishes their operational features.

The most practical units for optical communication use operate in the near-infrared spectrum (0.8 to 0.9 μm) range and are the silicon pn and PIN diodes applied in the reverse-bias photoconductive mode. Our consideration of photodetectors will thus be limited to these two classes. The terminology PIN derives from the semiconductor construction where an intrinsic (I) material is used between the p-n junction of the diode.

The fundamental operational characteristic of a photodiode (PD) is shown in Figure 2-21, where the current vs. bias voltage relationship is plotted. The parameter of the plot is incident light radiation. For example, curve (1) may represent the current voltage characteristic with no light impinging on the device. The current output under these conditions is known as the dark current. As light is incident on the device, the operation point will shift to curve (2). With increasing light intensity, operation shifts to curve (3), etc. This view of the etector is consistent with the quantum nature of the device, or

the concept of a "photon bucket". The output current of the device is proportional to the number of photons received per unit of time.

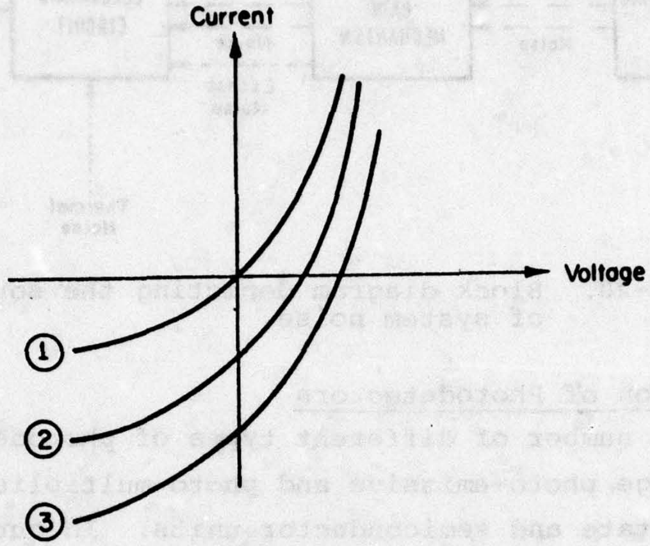


Figure 2-21. Response characteristics of photovoltaic devices.

The self-generation of voltage in a photodiode is accomplished as follows: The photogenerated holes and electrons diffuse across the p-n junction creating a region of high electric field at the interface. If the external circuit has a resistance which is considerably less than that of the junction, then most of the carrier flux appears in that resistor as signal current. The frequency response is determined by the drift velocity of the free carriers in the junction region. When the device is subjected to reverse bias, as in Figure 2-22, light impinging on the junction produces a linear increase in current.

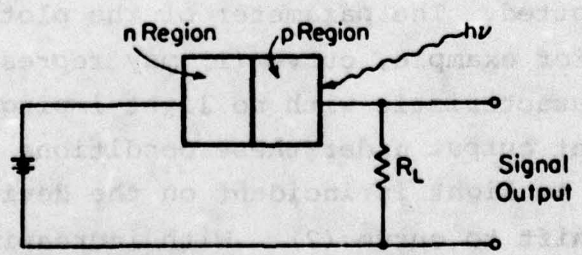


Figure 2-22. Application of reverse bias to a semiconductor photodiode.

Internal gain is achieved in a photodiode by applying an external voltage sufficient to extend the high field region into the two regions adjoining the junction. With the increased width of the field region, accelerated carriers have a good chance of colliding with semiconductor atoms, freeing even more carriers. This multiplication process may reach a value of 100 or more before it generates significant excess noise. The PIN structure improves the performance of the devices, since the intrinsic region is tailored to meet particular drift and multiplication effects. Internal gain in the detector is desirable since it precedes the electronic amplifier, in which thermal noise (generated in the resistive elements) is amplified with the signal. Thus, internal gain can preclude the possibility of operating in the thermal-noise-limited regime.

Consideration of internal gain in the photodetector serves to introduce the second class of devices which we will consider; namely, the avalanche photodiode (APD). When broadband detection of weak optical signals is required, current gain in the detector is essential. For these situations, the designer must generally turn to the APD as the choice in the receiver system. The APD is a more expensive component than the PD, and requires a greater complexity in bias circuits and/or power supplies. In addition, the current gain feature is usually synonomous with generation of excess noise (see fig. 2-20). However, the gain can usually be adjusted to a value that will yield a net improvement in the overall SNR (Gallawa, 1976). This will be seen in a later discussion in which the concept of optimum gain is introduced.

The APD is a semiconductor device designed specifically to produce internal current gain under control of the applied bias voltage. For a photodiode operating with low-reverse bias voltage, no carrier multiplication takes place. However, avalanching (carrier multiplication) occurs if the reverse bias voltage is increased sufficiently that the energy will excite new electron-hole pairs in the device. As noted before, significant current gain can be achieved, but at the expense of the introduction of

excess noise. If the bias voltage is increased beyond a critical value known as the dark breakdown voltage, the effectiveness of the gain is reduced because the noise power begins to increase faster than the signal power.

Gains on the order of 100 are possible. The actual values achieved depend on material, geometry of the device, and the methods by which avalanching takes place.

b. PIN Photodiodes

Commercial PIN diodes are available for detecting optical wavelengths in the range 200 nm to 1100 nm. Their peak responsivity is in the vicinity of 800 to 900 nm for silicon devices, with a range on the order of 300 to 600 μA/mw as noted in Figure 2-18. Minimum detectable signal level is on the order of 5×10^{-15} W. They have a wide dynamic range and good linearity properties. Inexpensive units can be expected to have a dynamic range of 8 to 10 orders of magnitude with low reverse bias voltages. Typical operational bias voltages range from 3 to 100 v.

The light sensitive or active areas of the units are typically a few mm^2 to the order of 1 cm^2. They generally have a uniform responsivitiy over the entire active area, and are quite stable with time and temperature. However, there is a response characteristic associated with these devices that should be noted. Although transient response time (switching speed) for the surface region and the depletion region is quite fast (on the order of 1 ns or less), the response time associated with the bulk diffusing region of the structure is much slower (on the order of 1 μs). Thus, the overall transient response is quite fast over about 90% of the transient, but becomes slow or sluggish over the "tail", or the remaining 10% of the time. The response time is sometimes specified only for the 90% response, or excluding the "tail effect" (see for example, the entries in Table 2-7). This feature can lead to intersymbol interference in a digital system as the "tail" of the response can spread in time to become significant in magnitude during the next bit-time slot.

PIN diodes are typically packaged in modified versions of standard TO-5 and TO-18 cans, with either flat glass or convex lenses. There are, however, a few special-package designs, including those specifically developed for fiber-optic applications where the detector is mounted in a connector shell with a fiber attached (fiber pigtail). A sketch of such a unit is shown in Figure 2-23, where a standard BNC-type connector houses either an LED or a PIN diode. Although in this discussion we have purposely avoided considering specific device architecture, there is one special feature of some PIN diodes and APD's that should be noted. That is the addition of a so-called guard-ring to the structure. Without going into physical detail, the primary purpose of this structure is to lower the dark current leakage from the unit, and consequently, to improve the total noise performance. The guard ring functionally forms a second diode structure which shunts the leakage currents away from the load resitance of the active photodiode. This will be seen in typical circuitry presented in a later section. Characteristics of typical photodiodes with and without the guard ring are shown in Figure 2-24. The improvement in dark current reduction for the units with larger active areas is not as great, since bulk leakage current increases directly with larger active areas.

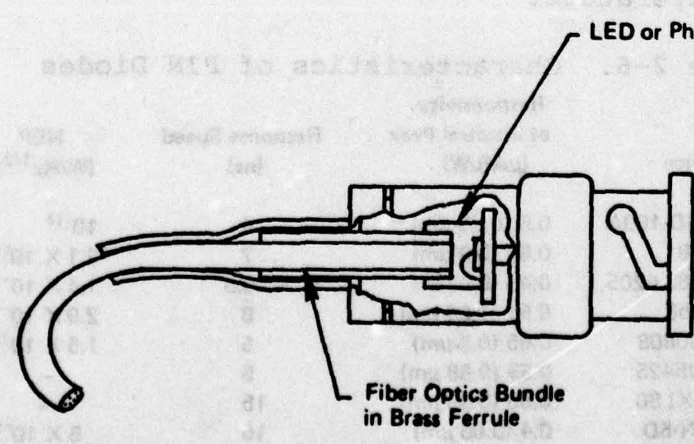


Figure 2-23. A fiber-optic termination using a BNC type connector (Hoss & Weigl, 1975).

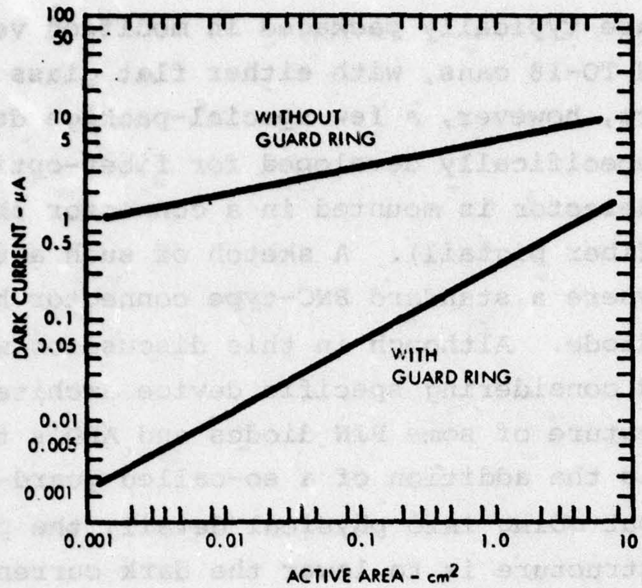


Figure 2-24. Dark current of typical photodiodes vs. active area (EG&G, 1977).

A few typical PIN diode characteristics are shown in Table 2-6, where the data are taken directly from manufacturers' data sheets and summaries (A.D. Little, Inc., 1976). Prices for these and similar units during 1976 were found to range from $5 to nearly $200 in small quantities. More detailed specifications and later price information may be found in more current manufacturer's literature.

Table 2-6. Characteristics of PIN Diodes

Manufacturer	Device	Responsivity at Spectral Peak ($\mu A/\mu W$)	Response Speed (ns)	NEP ($W/Hz^{1/2}$)	Bias (V)
EG&G	SGD-100A	0.5 (0.88 μm)	4	10^{-13}	100
Harshaw	538	0.62 (0.9 μm)	7	2.1×10^{-13}	100
Hewlett-Packard	5082-4205	0.45 (0.9 μm)	< 0.5	1.4×10^{-14}	15
Infrared Industries	7258	0.51 (1.06 μm)	8	2.9×10^{-13}	–
RCA	C30808	0.65 (0.9 μm)	5	1.5×10^{-13}	45
Spectronics	SD5425	0.55 (0.88 μm)	5	–	45
TI	TIXL80	0.55 (0.95 μm)	15	–	100
UDT	PIN-5D	0.4 (0.85 μm)	15	5×10^{-13}	50

(Source: A.D. Little, 1976)

To summarize this section, the following are considered to be the significant advantages and disadvantages of the PIN diodes:

Advantages

1. good linearity properties,
2. low to moderate NEP ratings,
3. moderate BW capabilities to the order of 50 - 100 MHz,
4. large dynamic range,
5. high responsivity in the 800 to 900 nm wavelength band,
6. good reliability and environmental characteristics.

Disadvantages

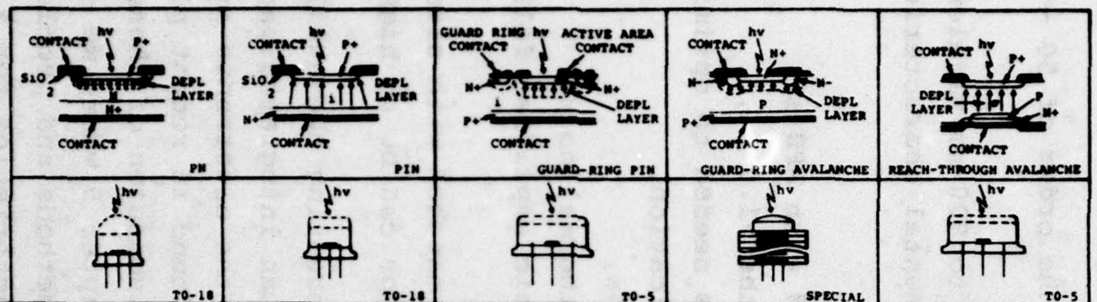
1. no internal gain (as compared with APD's),
2. low responsivity at wavelengths >1.0 μm,
3. special facrication processes needed to optimize package for fiber-optic application,
4. higher dark current than APD's,
5. application usually implies thermal noise limitation, based on electronic amplifier following optical detection,
6. active area size is not well matched with size of coupled fibers; coupling losses can be as high as 5 dB.

Manufacturing trends today are increasing the availability of complete detector modules, that is, an integrated package containing both the detector diode and the electronic amplifier circuitry. A few such modules can be found in recent product literature. We choose to delete any discussion of these modules at this point, and consider them in Chapter 5 where we discuss the topics of electro-optic interface methods and problems.

An informative tabulation of characteristics for a few PIN photodiodes and APD's has been presented by Casper (1975). His tabulation is presented in Table 2-7. It provides both a summary of the PIN device characteristics, and an opportunity to compare these with two types of APD's.

Table 2-7.

0.8-0.9 μm PIN Silicon Photodetector Diodes



	PIN (TO-18)	PIN (TO-18)	GUARD-RING PIN (TO-5)	GUARD-RING AVALANCHE (SPECIAL)	REACH-THROUGH AVALANCHE (TO-5)
NEP ($w/\sqrt{Hz}$)	14×10^{-14}	15×10^{-14}	8.5×10^{-14}	1.6×10^{-14}	1×10^{-14}
DARK CURRENT (AMPS)	20×10^{-9}	30×10^{-9}	10×10^{-9}	6×10^{-11} (BULK) 2×10^{-9} (SURF.)	$<1 \times 10^{-10}$ (BULK) 1×10^{-7} (SURF.)
QUANTUM EFFICIENCY	0.87 (EXCLUDING TAIL) 0.93 (INCLUDING TAIL)	0.9	0.9	0.37 (EXCLUDING TAIL) 0.66 (INCLUDING TAIL)	0.85
0.707 BANDWIDTH (MHz)	270	5[illegible]	70	800	175
SPEED (ns) (EXCLUDING TAIL)	1.3 (EXCLUDING TAIL)	6.5	5	0.5	2
REVERSE BIAS VOLTAGE	135	45	125	170	335 (M = 120)
SENSITIVE AREA DIAM (LENS EFFECT EXCLUDED (INCHES)	0.05	0.1	0.1	0.030	0.032
CAPACITANCE (pF)	3.1	6.0	4.0	8.0	2.0

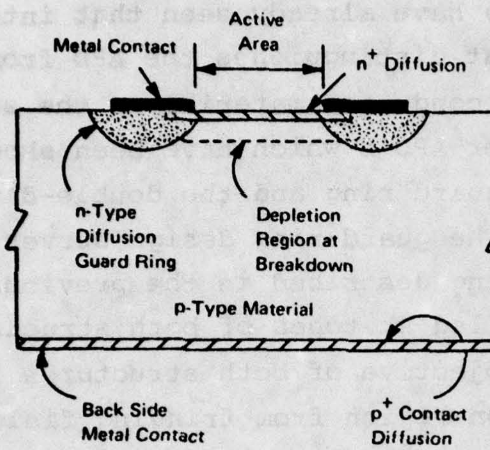
(Source: Casper, 1975)

c. Avalanche Photo Diodes (APD)

The APD is the second classification of photodetectors that will be considered. We have already seen that internal current gain is the feature that distinguishes the APD from the PIN diode, since their semiconductor material is the same. There are two basic structures for APD's which have been shown in Table 2-7. They are known as the guard ring and the double-diffusion "reach-through" structures. The guard-ring design serves the same purpose as the guard ring described in the previous sections for PIN diodes. More detailed sketches of both structures are shown in Figure 2-25. The objective of both structures is to protect the critical (active) pn-region from fringing fields that cause avalanching to occur at lower electric fields. In the reach-through structure, photons are absorbed in the thick intrinsic (π region) layer while electrons are swept toward the pn-junction where avalanching takes place in the high-field region. Note in the sketch of Figure 2-25(b) for the reach-through structure that the edge of the junction is protected by extending the n material deeper into the π-region.

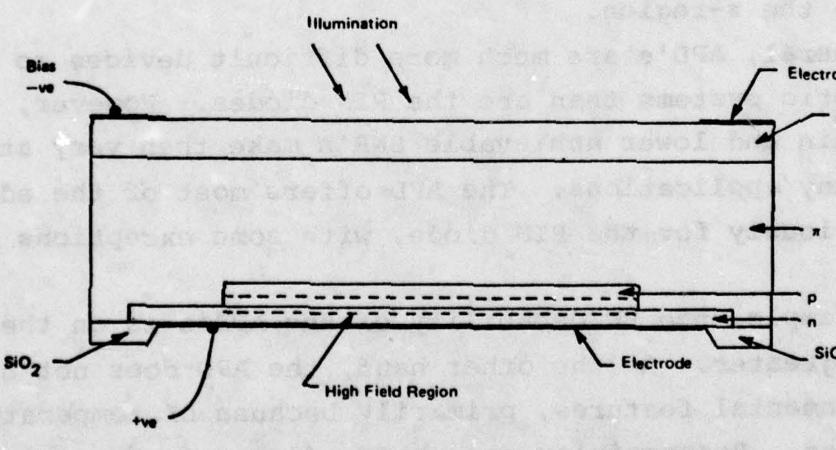
In general, APD's are much more difficult devices to apply in fiber-optic systems than are the PIN diodes. However, their inherent gain and lower achievable SNR's make then very attractive for many applications. The APD offers most of the advantages listed previously for the PIN diode, with some exceptions in both directions.

For example, the BW capability of the APD's is on the order of 5 times greater. On the other hand, the APD does not exhibit good environmental features, primarily because of temperature instabilities. Responsivity can change (due to changes in internal gain) significantly with temperature. Measured characteristics of a device are shown in Figure 2-26. These curves indicate how the gain of a unit may be established by careful control of the bias voltage, but also show how operating temperature changes can drastically change the responsivity at fixed bias



(a) Graded guard-ring structure.

(Electronic Design, July 19, 1973, p. 69)



(b) Double-diffusion reach-through structure.

Figure 2-25. Structure sketches of some typical APD detectors.

levels. Therefore, the requirement for temperature compensation of the device becomes evident. This is the first of two aspects that complicate the use of the APD.

The second application problem can also be noted to a degree from the abcissa scale in Figure 2-26, i.e., the relatively high bias voltage required for this device. The lowest voltage in Figure 2-26 is seen to be near the highest value required for most PIN diodes, and some APD's require bias voltages over 1000 volts. Perhaps these application problems are not too serious when the APD is the selected component at terminal points in a communication system. In this environment both problems are easier to handle, since temperature can be controlled or compensated for and the high-voltage source does not present a space or maintenance problem. However, in many systems, particularly in wideband or high data-rate applications, repeaters are required in the design. Obviously, repeater units should be as simple and environmentally stable as possible to enhance lifetime and to reduce maintenance to a minimum. The two requirements in this application are incompatible as far as the APD is concerned. The gain and bandwidth features may be needed to meet the communications objective at the expense of complicating the repeater design and implementation.

The characteristics of a few typical APD's are given in Table 2-8, where again the price information is based on manufacturers' listings for 1976. It is included only to provide a frame of reference and for comparative purposes. Comparing these figures with the price range quoted for PIN diode detectors, we note a correlation with bias voltage; the APD price picks up where the PIN diode leaves off.

The primary advantages and disadvantages of the APD detector have already been stated. In addition to these there are a few others that are important:

<u>Advantages</u>

1. high responsivity,
2. lower effective noise power (NEP),

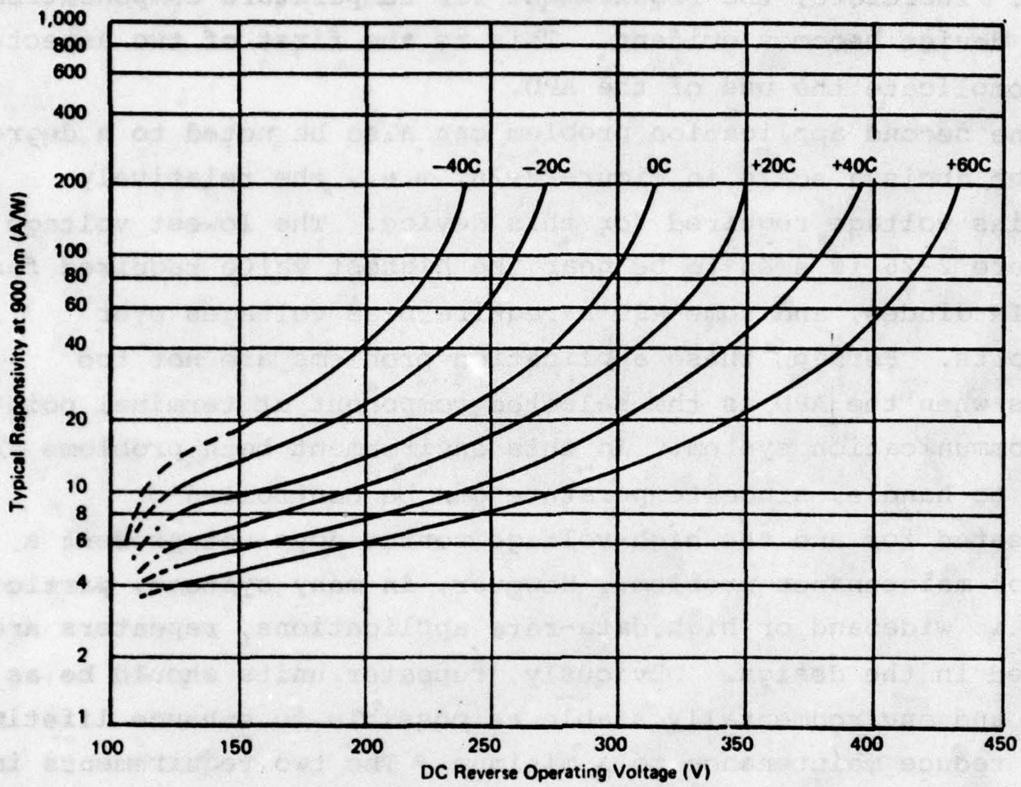


Figure 2-26. Effect of temperature on the responsivity of an APD (Optical Cable Communications Study, Report AD/A-016846, Rome Air Development Center, July, 1975).

Table 2-8.

CHARACTERISTICS OF SOME APDs

Manufacturer	Device	Bias Voltage (V)	Responsivity at Spectral Peak (μA/μW)	Bandwidth (MHz)	Price ($)
EMI/Gencom	S30500	166	37 (0.88 μm)	200	195.00
G.E.	50 EHS	2000	100 (0.9 μm)	100	425.00
RCA	30817	375	16 (1.06 μm)	200	160.00
RCA	30884	275	63 (0.9 μm)	250	225.00
TI	TIXL59	100	15 (0.78 μm)	500	170.00

(Source: A.D. Little, 1976)

3. wider BW,
4. smaller active areas.
5. no "tail effect" in transient response,
6. faster response time,
7. avoids thermal-noise-limited operation.

Disadvantages

1. operational requirements noted above,
2. current packaging is not entirely compatible with fiber-optic applications.

As in the case of PIN diodes, some manufacturers are improving the design of APD units for more adaptable use in fiber-optic systems. Also, integral modules are becoming available where the APD is incorporated in a complete package containing the temperature control circuitry, compensation circuits, and the electronic interface amplifier. These modules are considered briefly in Chapter 5, and some commercial examples will be found in recent product literature.

d. SNR Considerations

Gallawa (1976) has analyzed the various noise sources and currents for a variety of optical detectors, and given a general expression for the solution of the required optical power to yield a specified signal-to-noise ratio (SNR). It is the purpose of this section to summarize these results, and present them in a simplified but useful form. We include only two limiting forms derived in Gallawa's treatment that are applicable to the two classes of detectors considered in this section. The equations presented are not intended to provide accurate results, but only to yield approximate values.

The basic solution for the required optical power is given as:

$$P_o = \frac{FBh\nu(SNR)}{2\eta m^2}\left\{1 + \left[1 + \frac{4I_{eq}m^2}{FqB(SNR)}\right]^{1/2}\right\} \quad (2\text{-}4)$$

where I_{eq} accounts for all external noise currents:

$$I_{eq} = I_b + I_d + \frac{2kT_{eff}}{FqM^2R_{eq}} . \qquad (2\text{-}5)$$

Some of the terms in these expressions have been defined previously. However, we define all terms as follows:

F - the excess noise factor (dimensionless)

B - bandwidth (Hz)

h - Planck's constant (6.626×10^{-34} joules·s)

ν - frequency (Hz)

η - quantum efficiency (dimensionless)

m - depth of amplitude modulation (dimensionless)

q - electron charge (1.6×10^{-19} coulomb)

I_b - shot noise current (amps)

I_d - dark (noise) current (amps)

k - Boltzmann's constant (1.38×10^{-23} joules/K)

M - current gain factor (dimensionless)

T_{eff} - effective temperature in K (290°)

R_{eq} - equivalent load resistance (ohms).

The two limiting cases considered are for the following conditions:

$$\frac{4I_{eq}m^2}{FqB(SNR)} << 1 , \qquad (2\text{-}6)$$

$$\frac{4I_{eq}m^2}{FqB(SNR)} >> 1 , \qquad (2\text{-}7)$$

where Equation (2-6) represents the case where noise in signal dominates (say for APD detectors), and Equation (2-7) represents the case where external or thermal noise is dominant.

For noise-in-signal limits, where $I_{eq} = 0$, Equation (2-4) may be reduced to the approximation,

$$P_o = \frac{Fh\nu B}{\eta} \left[\frac{(SNR)}{m^2} \right] , \qquad (2\text{-}8)$$

For the external noise limit of Equation (2-7), the corresponding approximation becomes,

$$p_o = \frac{Fh\nu}{\beta}\left[\frac{SNR}{m^2}\right]^{1/2}, \tag{2-9}$$

where

$$\beta^2 = \frac{F\eta^2 Bq}{I_{eq}} . \tag{2-10}$$

The importance of β, which has been called the retrieval efficiency of the receiver, can be seen by examining the form of Equations (2-8) and (2-9). The definition of β is such that it parallels closely the definition of quantum efficiency of the detector. Indeed, the ratio β/η depends on the ability of the receiver to retrieve the incoming information.

At least two of the terms in the above expressions need further explanation. For example, η was introduced earlier as a proportionality constant that is frequency dependent. It is a value that can be estimated from Equation (2-3) for a given responsivity and the frequency of interest.

The excess noise factor F has been shown to be unity for detectors without gain, such as PIN diodes. For the APD devices with current gain, F is proportional to M as

$$F = M^{\gamma} . \tag{2-11}$$

For current gains in the range $1 \leq M \leq 200$, $\gamma = 1/2$ is a good approximation to use in Equation (2-11).

The expressions presented here have been used to develop a graphical solution for p_o as a function of SNR for a digital system. These results are seen in Chapter 3.

Carrying this discussion one step further will illustrate the concept of optimum gain, which is also shown graphically for a digital system in Chapter 6. The SNR expression derived by Gallawa (1976) contains M^2 in the numerator and FM^2 in the denominator. The FM^2 term multiplies the excess noise term in the

denominator. Thus, as M is increased, there is a point of optimum gain ($M = M_o$) where the denominator term will increase more rapidly than the numerator, and no further improvement in SNR can be expected. Further increase in gain will cause SNR degradation.

For optimum gain M_o, it can thus be shown that the SNR is given by

$$SNR = \eta^2 M_o^2 R_{eq} \frac{\left[\frac{q}{h\nu} m\, p_o\right]^2}{16\, kT_{eff} B} . \tag{2-12}$$

In this form, we note the significance of the term $\eta^2 M_o^2 R_{eq}$, which is sometimes used as a figure of merit for photodetectors. All other terms in Equation (2-12) are beyond the control of the communications engineer.

2-5. THE OPTICAL FIBER WAVEGUIDE

a. Introduction.

In the previous two sections we have presented summary discussions of those optical devices that provide the carrier source and the detection of optical signals. We now come to the heart of the transmission system itself, the optical fiber waveguide connecting the source and detector. In keeping with our original premise of presenting only the necessary information, we shall attempt to limit our discussion to the application concepts of this system component, and avoid wherever possible the background physics or manufacturing details. However, as was seen in discussing the source devices and detectors, it is sometimes necessary to consider at least elementary concepts in order to understand improvements achieved and/or being developed. These facets will be introduced where appropriate, and references furnished that will confirm conclusions and provide for deeper understanding of the topics.

Guided-wave technology is not new to the microwave engineer, and there are common features between the guided transmission of microwave and optical signals. To orient the reader to the newer concept of guided optical signals, we repeat here some of the introductory remarks of Gallawa (1976) to the subject.

We are concerned with a transmission medium which guides the signal-carrying electromagnetic field along a pre-determined path. This is in contrast to atmospheric propagation which is quite useful in many situations, but which introduces serious penalties, especially in inclement weather. In guided wave systems, a mechanical structure is required that restrict the transverse spread of the field and also protects the signal from the hostile atmosphere in some cases. The structure can take any of various forms, each having advantages and disadvantages. Again, the challenge of the design engineer is to weigh the various alternatives and to select the device best suited to the communication task. At low frequencies, the transmission line is usually composed of two separate conducting boundaries. Currents flow in the conductors and the wave is guided by virtue of the reactance exhibited due to the proximity of the two conductors. A single structure can be used to guide electromagnetic energy in either of two ways: (a) by reflecting from highly conducting walls, and (b) by refraction at gradients of refractive index.

In either case, the structure incorporates two different media and an associated interface between them. To analyze the capabilities of the waveguide, one must solve Maxwell's equations in each medium and use the continuity equations to determine precisely what happens at the interface. The interpretation of the resulting expressions provides the basis for the engineering design. Such things as loss, launching efficiency, signal distortion, and crosstalk can be understood in terms of those resulting expressions.

If an electromagnetic wave is guided by virtue of reflections from highly conducting walls, the guiding structure is called a closed waveguide; if the guidance is due to a gradient in the refractive index, the guiding structure is called an open waveguide. A coaxial cable and a metallic hollow tube are examples of closed waveguides; a dielectric rod suspended in free space is an example of an open waveguide. In the case of closed guides, standing waves are established in the transverse plane;

the standing waves define the modes which propagate within the waveguide. In the case of the open waveguide, an evanescent field distribution is established in the transverse plane and the mode is guided by the index gradient. Categorizing waveguides as closed or open is useful since many of the advantages and disadvantages of certain structures are typical of all structures in that category.

In a closed waveguide having perfectly conducting walls, the eigenfunctions (or modes) form an infinite discrete set, each mode having an eigenvalue which defines the propagation constant for the mode. The field in the guide can always be described in terms of those modes; a radiation field does not exist, and discontinuities and bends will lead to mode conversion but not to radiation. This is a simple but important concept, and it forms the basis of a key difference between open and closed waveguides. Since the field in the closed waveguide is not coupled to a radiated field, a free-space wave cannot be coupled into the waveguide; hence, the propagating modes are completely screened. Strictly speaking, this is true only for a waveguide made of perfectly conducting material; as the conductivity becomes finite, the modes which can be supported do not constitute a complete set and a continuous spectrum is required. This implies that a free-space wave would also couple into the waveguide region and screening would not be complete.

For practical purposes, closed waveguides, even those not made of perfectly conducting material, are completely screened and the field can be completely described in terms of discrete modes. In describing the propagation characteristics, then, one need only be concerned with mode conversion and reconversion, not with radiation.

For the open (optical) waveguides with which we will be concerned, the electromagnetic wave propagates without radiation along the interface between different media. In order for there to be no radiation, the interface must be perfectly straight in the direction of propagation and there must be no obstacles in

the vicinity of the interface. Thus, a perfectly straight dielectric rod in free space is an example of the open waveguides of interest. In particular, we will be concerned with open waveguides which support a surface wave; with regard to the latter, we content ourselves with the definition proposed by Barlow and Brown (1962): "A surface wave is one that propagates along an interface between two different media without radiation, such radiation being construed to mean energy converted from the surface wave field to some other form".

This definition is not precise; however, it will be sufficient for our purposes since the optical fiber waveguide with which we will be concerned supports surface waves in accordance with this definition.

We see immediately that a surface wave guided along an open waveguide may lose some of its energy to radiation and/or mode conversion when there is an obstacle, such as a support, in the vicinity of the waveguide. This may also happen while negotiating a bend. This is in contrast to the closed waveguide which is completely screened. In most open structures, the parameters can be adjusted so that the surface wave is very tightly bound to the interface and any disturbing object more than a few wavelengths away from the surface has negligible effects.

The reader will recall that the two-wire line is an open waveguide which has serious limitations at higher frequencies; the major drawbacks of that line, however, are the requirements for balance and uniform spacing. Single-wire open guides do not have these requirements.

Until very recently, the most important practical form of single wire open waveguide was the axial cylindrical surface wave structure, sometimes called the Goubau line or G-line. Today, the optical fiber is much more important and potentially much more useful. It was the G-line, however, that first demonstrated the utility of open waveguides in telecommunications.

The performance of a waveguide depends on four principal factors:

1. modal characteristics of the propagating wave,
2. the geometry of the guiding structure,
3. manufacturing tolerances, and,
4. materials used in manufacture.

These factors influence communications capability by virtue of their effect on the signal through

1. delay distortion,
2. signal distortion due to multi-mode operation,
3. signal energy loss owing to mode conversion and scattering, such loss being the result of manufacturing defects, and
4. signal dispersion due to the material characteristics.

These factors will be considered throughout the following discussions with respect to the types of optical fiber waveguides.

b. Classification of Optical Fiber Guides

There are actually two distinct classifications of optical fibers that are found to be useful. The first is based upon the application technology, i.e., single fibers vs. bundle fibers. The second is based upon structural differences that impact upon performance parameters and modal operation. The latter include variations in both materials and manufacturing processes. Obviously, some factors considered in the second classification are not unique to either of the first, but will overlap in the applications area.

c. Some Common Features of Optical Fibers

Before proceeding to specific classification factors and applications, we can examine briefly some common parameters and trends. For example, we have already considered the prime feature which is the driving force behind fiber development, and that is to lower the attenuation losses. Figure 2-2 was presented to illustrate the attenuation of high-silica materials vs.

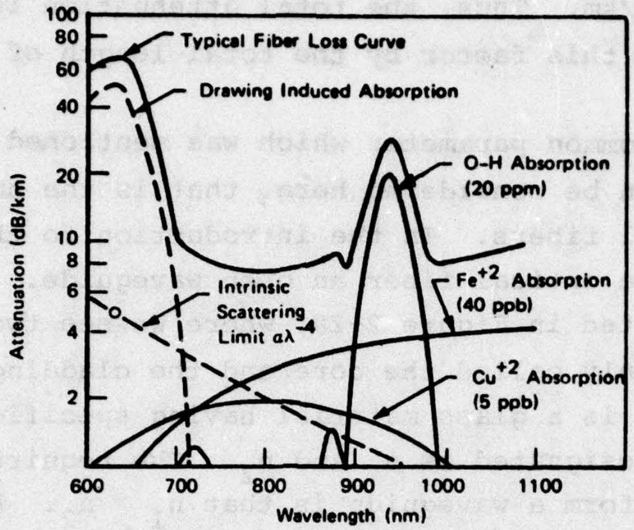


Figure 2-27. Loss characteristics of optical glass fibers (Jaeger, 1976).

wavelength of transmission. High-silica glass fibers represent the state of the art for low-loss application. Some experimental work with liquid-filled fibers has demonstrated that low attenuation can be achieved, but present consideration of both manufacturing and application problems render them impractical at this time. Figure 2-2 shows that the baseline of the attenuation characteristic is due to a scattering phenomenon in the material. Scattering however is accompanied by absorption losses that account for the variations in the solid-line characteristic of Figure 2-2. These various added losses are caused by absorption in impurities in the material. The various origins of these losses are shown in Figure 2-27 for a particular fiber. We will not discuss these loss contributors in detail, but merely point out that the significant contributors are Fe and Cu impurities, and the OH absorption feature. The composite of these is shown as the typical fiber loss curve, which again shows the minimum loss region to be between 700 and 900 nm wavelengths and above 1.0 μm. Most materials research is devoted to reducing this composite curve so that it comes closer to the intrinsic scattering limit. Material losses are quite uniform as a function of

length of fibers, and the attenuation factor is always specified in units of dB/km. Thus, the total attenuation is simply found by multiplying this factor by the total length of the fiber in question.

Another common parameter which was mentioned earlier but not defined can be considered here: that is the numerical aperture (NA) of optical fibers. In the introduction to this section we consider the optical fiber an open waveguide. Its geometry is depicted in Figure 2-28, where we see two concentric sections commonly called the core and the cladding. Each of these sections is a glass material having specific refractive index values designated as n_1 and n_2. The requirement for such a dielectric to form a waveguide is that $n_1 > n_2$. From this we can see that the cladding material is not essential, as the refractive index of air is unity ($n_2 = 1$) and we could select a core material with $n_1 > 1$ to form a guide. However, in this situation for an open guide, the electromagnetic field would not be constrained. It would extend beyond the material/air interface. In supporting such a guide, both radiation and reflection losses would occur where the supports came in contact with the core. By including the cladding material around the core this problem is alleviated. The cladding material can be made sufficiently thick (large radius) so that the fields will decay (exponentially) to essentially zero before reaching the cladding/air boundary. In this manner, the fields are completely constrained to the two-component guide, and no significant radiation loss or reflection is possible at the support points.

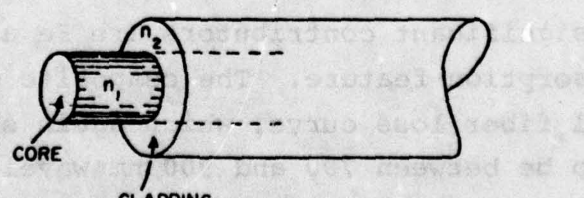


Figure 2-28. Sketch of a cladded glass fiber waveguide.

A second very important reason for including a cladding around the core is related to the numerical aperture (NA) and the number of propagation modes which the guide will support. As we will see later it is sometimes quite desirable to limit the number of propagation modes supportable by the guide. For an unclad guide, the number of modes will increase as a function of $(a/\lambda)^2$, where a is the radius of the core and λ is the wavelength. In order to restrict modes, the radius of the core must be kept small, which makes the core material more difficult to form and more vulnerable to structural damage in handling. It can also be shown that the number of modes increases with the square of the so-called normalized frequency V, which is given by (Gallawa, 1976)

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2} \quad . \tag{2-13}$$

From Equation (2-13) we introduce the definition of numerical aperture as

$$NA = \sqrt{n_1^2 - n_2^2} \quad . \tag{2-14}$$

This term may also be defined from ray theory and Snell's law of refraction (Gallawa, 1976), but we will leave this development to the reader to pursue. The important features of the term can be stated briefly using only Equations (2-13) and (2-14).

First, from Equation (2-13) it is seen that the number of propagating modes can be limited by either controlling the core radius a and/or limiting the NA to small values. Thus, in combination, we note that we may increase a for improved core drawing and structural properties if we can simultaneously reduce the NA. The NA is reduced by restricting the difference between the refractive indices of core and cladding to smaller and smaller values, keeping in mind the requirement that $n_1 > n_2$.

NA is an effective measure of the light-accepting property of a fiber. We can gain insight to this aspect and some additional

terminology which we will encounter later, by simple ray theory consideration. This will also enhance the meaning of modal propagation in the fiber without recourse to mathematical theory. Figure 2-29 illustrates the geometry of a light ray impinging on the end of a clad fiber. One ray (solid line) shows the effect of the ray entering at angle ϕ_1' such that a complete reflection takes place at the interface of core and cladding. The critical angle ζ_c for this reflection to occur is given by

$$\sin \zeta_c = n_2/n_1 \tag{2-15}$$

where the angle ζ is defined in the figure. The incident ray is assumed to be in a region of refractive index n_o. The NA can also be derived from this approach, and is found to be (Gallawa, 1976)

$$NA = n_o \sin \zeta_c \quad . \tag{2-16}$$

From Equation (2-16) we see that NA is proportional to the sine of the incident angle of the impinging ray. If the geometry is extended to the solid case, the angle ϕ_1' forms a cone (an acceptance cone) or solid angle in which any incident ray will be reflected internally at the core/cladding interface. A ray entering the fiber at an angle greater than ϕ_1' (dashed line in Figure 2-29) will strike the interface at less than the critical angle ζ_c, and will be only partially reflected, and a refracted ray will be launched in the cladding material of lower index. The geometry in this figure is based on the assumption that $n_1 > n_o$. Since in the normal case we assume $n_o = 1$ for air, and the refractive index for glass is about $n_1 = 1.5$, this geometry holds.

The modal features of propagation in the guide can be visualized from simple ray theory by considering the number of incident rays that will fall within the acceptance cone. Each one will propagate down the guide with a series of reflections at the core/cladding interface. The larger the internal angle of

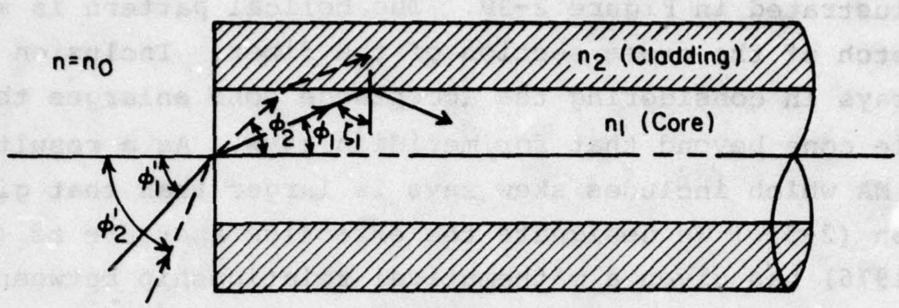


Figure 2-29. Ray geometry in a step-index optical fiber.

incidence (ϕ_1 in Figure 2-29) the larger the number of reflections there will be per unit length. Since there is an associated loss with each reflection, the higher modes (more reflections) will suffer additional loss in transmission. Also, the higher modes mean longer total path lengths that translate into additional attenuation loss. It can be seen that both of these considerations will increase as the core diameter of the fiber is decreased. For example, there will be many more reflections for a given angle of internal incidence as the core diameter becomes less. This is a seeming paradox with an earlier statement, which suggested smaller core diameters to limit the number of modes. However, it is merely another way in which the importance of NA as a figure of merit can be emphasized. Another reason has been added to the list given above for larger core size. To compensate for this, the NA should be made as small as possible. For small values of NA we note from Equation (2-7) that ϕ_1' (and consequently ϕ_1) will become smaller, and will thus limit the acceptance angle and the propagating modes.

In the above illustration, where we have used simple ray theory, some modification is necessary to account for skew rays. Skew rays are those that do not follow the straightforward meridian paths (in a plane which includes the optical axis of the fiber), but enter the guide in such a way that reflections occur off the meridian plane. Consequently, the ray follows a somewhat helical path as it traverses the guide. The geometry for a skew

ray is illustrated in Figure 2-30. The helical pattern is shown in the sketch of the cross section of the fiber. Inclusion of the skew rays in considering the acceptance cone enlarges the solid-angle cone beyond that for meridian rays. As a result, the effective NA which includes skew rays is larger than that given by Equation (2-5). We designate the effective aperture as $(NA)_s$. Gallawa (1976) has given a mathematical relationship between NA and $(NA)_s$. However, for our purposes the graphical relationship shown in Figure 2-31 will suffice. The ratio of $(NA)_s/NA$ is plotted vs. the NA calculated with either Equation (2-14) or (2-16). For example, we see that $(NA)_s$ has a value of approximately 0.625 for a NA = 0.5; $(NA)_s$ is larger than NA.

The final characteristic to be considered that is common to all fibers is the dispersion property. We will find in Chapter 6 that dispersion is a very significant property in system design since it can become the limiting factor in performance. Dispersion in transmission causes distortion to signals in the time domain. This leads to such problems as intersymbol interference in digital bit-streams. Thus, for high data rate systems, even though the attenuation factors are overcome and sufficient optical power is available at the detector, dispersion can cause performance degradation.

Dispersion in optical fibers is attributed to three distinct factors as follows:

1. waveguide,
2. material dispersion,
3. multi-mode transmission.

Waveguide dispersion is caused by variations in the electrical and physical dimensions of the waveguide, which give rise to phase variations as a function of frequency. Optical sources do not generate a strictly monochromatic signal, but produce a signal of finite spectral width. If phase distortion is encountered in propagating through the guide, the received signal will be distorted in magnitude and will spread in frequency. Material

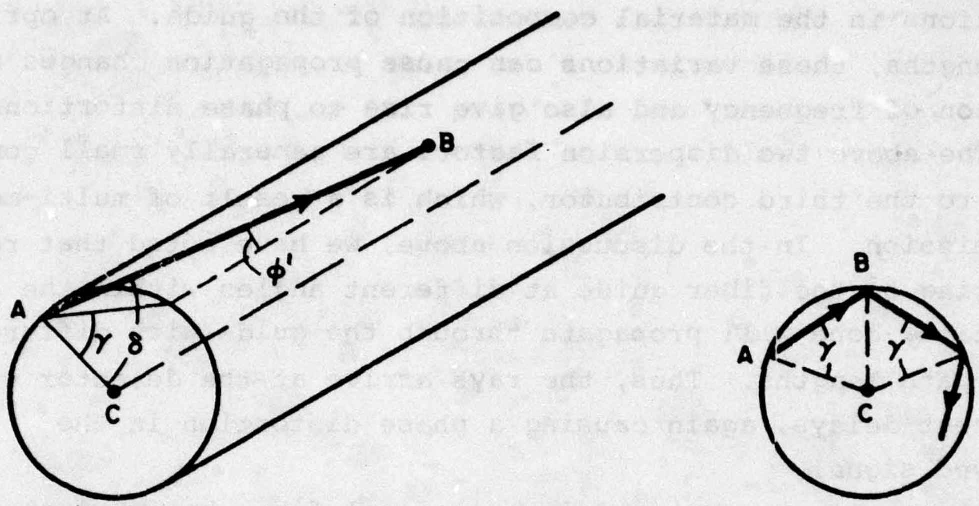


Figure 2-30. Skew rays in a circular optical fiber.

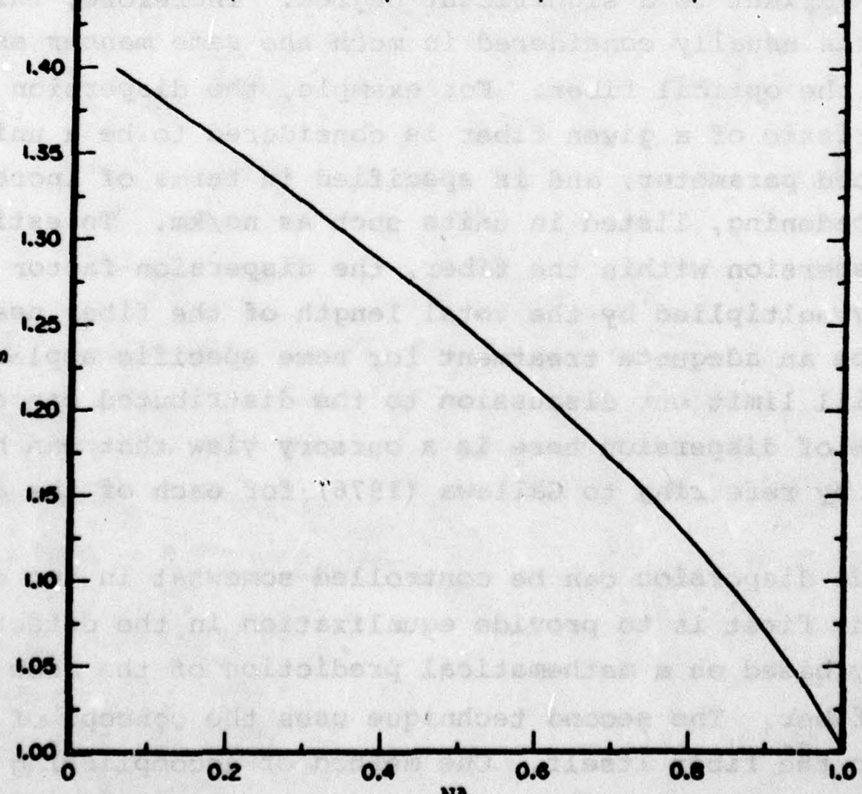


Figure 2-31. The variation in the ratio of $(NA)_s/NA$.

dispersion is caused by (as the name implies) the impurities and variations in the material composition of the guide. At optical wavelengths, these variations can cause propagation changes as a function of frequency and also give rise to phase distortions.

The above two dispersion factors are generally small compared to the third contributor, which is a result of multi-mode transmission. In the discussion above, we have noted that rays impinging on the fiber guide at different angles within the acceptance cone will propagate through the guide with different total path lengths. Thus, the rays arrive at the detector with different delays, again causing a phase distortion in the received signal.

Dispersion encountered in an optical fiber has an important distinction from that in radiating systems that are familiar to the microwave engineer. In the optical fiber, the dispersion is not time-variant to a significant degree. Therefore, this property is usually considered in much the same manner as attenuation in the optical fiber. For example, the dispersion characteristic of a given fiber is considered to be a uniformly distributed parameter, and is specified in terms of incremental pulse broadening, listed in units such as ns/km. To estimate the total dispersion within the fiber, the dispersion factor specified is merely multiplied by the total length of the fiber used. This may not be an adequate treatment for some specific application, but we will limit our discussion to the distributed concept. The treatment of dispersion here is a cursory view that can be expanded in depth by referring to Gallawa (1976) for each of the above factors.

Modal dispersion can be controlled somewhat in two distinct ways. The first is to provide equalization in the detector circuitry based on a mathematical prediction of the mode dispersion for the fiber. The second technique uses the concept of mode mixing in the fiber itself. One method of accomplishing mode mixing is by varying (purposely) the diameter of the fiber core in manufacture. In this technique, mode conversion is encouraged

to the extent that it effectively reduces the pulse spreading. If a continuous exchange of power takes place along the waveguide, there is a net delay which depends on the weighted average of the delays of all the modes. Some of the power is carried by low order modes at high group velocities and some by high order modes at low group velocities. As continuous mode shifting takes place, there is an average velocity for power transfer and an average pulse width which is less than would exist in the absence of power shift. Neither of these schemes will be discussed further. They are noted only for completeness and to alert the reader of their existence.

d. Optical Fiber Materials and Fabrication

Detailed consideration of either optical fiber materials and fabrication techniques are outside of the scope of this document. However, the user should be aware of the materials in common use and a few of the fabrication methods used in order better to understand product literature and application features.

The most common materials in use at this time are silica and various compound glasses. They are favored because of their comparitively low losses, where the attenuation factor γ is on the order of 20 dB/km or less. Unfortunately, small γ and small NA's are not inherently compatible in these materials. The NA's usually range greater than 0.3. However, most of the research and product-development activity is centered on improving these factors through manufacturing processes. Attenuation is lowered by improving the purity of the materials, and NA's are being reduced to the point where production of single-mode (SM) fibers is becoming more practical.

The production of single-mode fibers obviously alleviates the multimode dispersion problem discussed in the previous section. In addition, other processes are being used to produce multi-mode fibers that have less dispersion. The latter are commonly referred to as the graded index (GI) fibers. In this structure, the refractive index of the fiber material is graded

in such a way that light rays are subjected to a continuous refractive bending as they propagate in the guide. This is contrasted to the step index (SI) fiber which we have considered in the previous discussions. For example, the sketch of a cladded-core fiber shown in Figure 2-29 is a step-index fiber. The terminology for SI stems from the fact the refractive index between core material and the cladding makes an abrupt (step) change at the interface. In contrast to this refractive structure, the GI fiber characteristic is sketched in Figure 2-32. The sketch at the left illustrates the uniform (parabolic type) change in refractive index as a function of the cross-section distance across the diameter of the fiber. The flat tails of the characteristic represent the step change at the boundaries of the fiber.

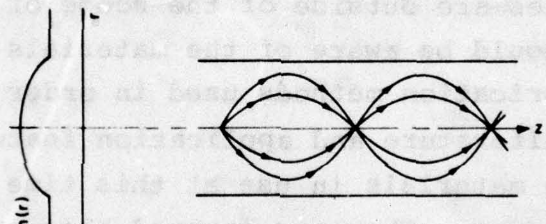


Figure 2-32. The refractive index structure and ray-path geometry in a graded index optical fiber.

The right-hand part of Figure 2-32 is a sketch of the ray paths. The path of a light ray in such a fiber will not be a straight line, but will be curved in such a way that the ray forms a periodic oscillation about the axis, as shown in the figure. The mean axial velocity over a full oscillatory period must be constant for the phase terms to add properly. This is equivalent to requiring a constant optical path length for all ray paths. The mode dispersion improvement of such a guide is obvious if in fact all modes do travel equal path lengths. Of course, this picture of a GI fiber is idealized, and not met in practical fibers. However, considerable improvements have been made in the dispersion properties over SI fibers.

Fabricating processes used in producing optical fibers include the following:

1. chemical vapor deposition,
2. doped diffused silica,
3. various fiber-drawing techniques.

As stated previously, it is beyond the scope of this report to discuss these various processes. The names themselves are somewhat self-explanatory, and convey some concept of the processes involved.

Since the refractive index of a GI fiber is a continuous function, the definition given by Equation (2-14) for NA is not readily applicable. However, the NA factor is still useful as a figure of merit for these fibers. A modification of Equation (2-14) can be made, where the difference between the two indices is replaced by the difference in the two limits of indices within the GI fiber. The expression for the refractive index of a GI fiber is given in Appendix A. It is found to be a function of the difference in the limit value of the graded index and the index of the cladding, given by (measure of contrast)

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}, \tag{2-17}$$

where n_1 is now the index of the fiber at r=a, and n_2 is again the index of the cladding. The graded index is also a function of the profile parameter, which is also discussed in Appendix A.

Another important feature of the GI fiber should be noted. It was stated in reference to Equation (2-13) that the number of modes supported within the fiber is a function of the normalized frequency parameter, V. For an SI fiber, the number of modes $N_s = V^2/2$. It can be shown that the GI fiber reduces this number by a factor of 2. In other words, for the GI fiber, $N_G = V^2/4$. In each case, V^2 is proportional to NA.

e. Optical Fiber Bundles.

The technology using optical fiber bundles is perhaps more advanced than that based on single fiber transmission. The bundle waveguide consists of a number of individual fibers bundled together to form a single waveguide. The objectives of the bundle technology are manifold:

1. to provide a high light-coupling and emitting area to the source and detector (respectively) taking advantage of the large cross section of the bundle,
2. to provide redundant transmission channels in case of fiber breakage,
3. to produce an inexpensive waveguide formed of less expensive commercial grade glass,
4. to provide a waveguide applicable to short-haul, narrow-bandwidth, low data rate systems.

The variations in the available bundle waveguides relate to packing methods and densities. The designs generally aim for a high packing fraction (ratio of fiber cross section area to total bundle cross section). Good mechanical protection is also desirable, at the same time allowing individual fibers to move with respect to each other for good flexibility.

Fiber-bundle technology is of limited interest in this document. Since the bundle guides have inherently high attenuation, and are limited in application to systems requiring a BW of 20 MHz or less, they are useful primarily over very short distances. For example, bundle technology is applicable to inter-rack systems, where it is desired to use fiber transmission for protection from EMI. Another significant application is in avionics systems, where EMI protection as well as reduced weight (compared to standard cabling) are important. In either case, the distances for practical application are relatively short.

Characteristics of a few fiber-bundle cables are given in Table 2-9. The attenuation property is listed in the usual manner, i.e., in dB/km. A glance at the tabulated values

is sufficient to dismiss these components; they do not achieve stated objectives for this handbook unless the transmission length is limited to the order of meters.

Table 2-9. Characteristics of Some Fiber-Bundle Cables

Manufacturer	Type	Attenuation (dB/km)	NA	Price ($/km)
American Optical	LGM-2-72	1300	0.56	16,950*
	LGM-5-72	1300	0.56	34,996†
Corning Glass	5019	600 (at 0.82 μm)	0.63	850
Pilkington	Hytran 100	100 (at 0.83 μm)	0.5	-
Rank Precision Industries	400 X	400 (at 9.8 μm)	0.54	30,000
Valtec	RT 03	400 (at 0.82 μm)	0.56	2,500
Fiberoptic Cable Corporation	QI-7-5	50 (at 0.82 μm)	0.25	4,000

*$31 for 6-ft cable.
†$64 for 6-ft cable.
Source: A.D. Little, 1976.

f. Single Fibers

In Section a, we have already discussed the primary features and parameters involved with single optical fibers. In addition, the two basic types of fibers in this category were introduced, namely, the step index (SI) and graded index (GI) fibers. However, within this class there is a variety of fibers commercially available that are made form different materials and that exhibit radically different characteristics. It is the purpose here to provide a summary of these fibers, and to add a few applications notes.

Table 2-10 presents the characteristics of some typical optical fibers in this class. Note that the attenuation factors listed are as low as 10 dB/km for several of the entries, and most of the dispersion factors listed are quite high relative to

the three lowest values given. The data in this table are representative of the selections available in 1976, but are typical of currently available fibers. A comparison of parameters given in the later product literature with those of Table 2-10 will convey a sense of the dynamic changes taking place in this field. Some fibers are available with attenuation factors as low as 5 dB/km (and even lower factors are projected).

Table 2-10.

Characteristics of Some Commercial Optical Fibers

Manufacturer	Type	α(dB/km)	Dispersion[a] (ns/km)		NA	Price ($/km)
Corning	Corguide-1152	10 (at 0.82)	GI	3	0.18	3,000
DuPont	Plastic PFX-P140R	470 (at 0.656 μm)	SI	–		2,300
Fiber Communications	S10	10 (at 0.8 μm)	SI	–	0.16	2,500
	S20	10 (at 0.8 μm)	SI	–	0.16	900
	–	250 (at 0.6328 μm)	SM	–	0.11	10,000
Fiberoptic Cable	Q1-1-10[b]	20 (at 0.82 μm)	SI	30	0.25	1,650
Galileo Electro-optics	Galite 3000	60 (at 0.9 μm)	SI	–	0.48	6,000
ITT	GS-02-10	12 (at 0.85 μm)	SI	30	0.25	–
	PS-05-40 (Plastic)	40 (at 0.79 μm)	SI	50	0.25	–
Valtec	MS05	10 (at 0.82 μm)	SI	30	0.2	2,500
	MG05	10 (at 0.82 μm)	GI	5	0.2	2,500
	SM10	20	SM	1	–	10,000
	PC05 (Plastic)	40	SI	40	0.22	2,000

[a]SI – Step Index
GI – Graded Index
SM – Single Mode
[b]Cable

(Source: A.D. Little, 1976)

Two particular entries in Table 2-10 are worth a special note to emphasize the most significant feature of a GI fiber. The type MS05 and MG05 fibers are seen to have the same attenuation and NA characteristics. However, the second type is a GI

fiber, and we note that the dispersion characteristic has been improved by a factor of 6 compared to its counterpart which is a SI fiber of the same size. Note also that the tabulation includes only one single mode (SM) fiber with nominal attenuation.

Application notes relative to the single fiber classification can be summarized as follows:

1. For systems requiring a low to moderate length-bandwidth product, the SI fiber can generally be used.
2. For large length-bandwidth products, the GI fiber is the logical choice, with smaller dispersion factors for the longer links. Examples of these choices are given in the appendices.
3. For short links, material choice includes
   - plastic coated silica (PCS),
   - plastic coated plastic (PCP),
   - all glass fibers.
4. PCP fibers exhibit high attenuation factors and are usually limited to applications less than 100 m.
5. PCS and glass fibers have attenuation factors as low as 10 dB/km.
6. Fibers which have higher NA's provide a better match to LED's for shorter link application.

The obvious best choice of material for the longer link requiring higher BW is the GI fiber fabricated from high purity doped silica.

g. Cable Structures

One of the areas with the least standardization in the optical fiber communications field is the area of cable design. Applications of the technology have not yet created a sufficient demand for cables from the industry that will permit the final evaluation of several designs to be made, i.e., field installation and long-term testing. Most of the structural and environmental

data available are based on laboratory testing, or applications involving short distances and limited operational time. For example, experience has just recently been gained in pulling optical fiber cables in lengths up to 1 km through standard underground facilities and building conduits. However, the technical literature indicates that advances are continuously being made, including applications requiring submerged cable.

Figure 2-33 presents a variety of cable configurations and structural features typical of those available at this time. The manufacturer of each type illustrated is identified in the figure; however, no endorsements should be implied. The most important mechanical features to evaluate in selecting a cable are:

1. tensile strength,
2. adequate strength-member selection,
3. bending radius,
4. support requirements,
5. environmental specifications,
6. length of continuous run available,
7. lengths that can be safely pulled in conduits and raceways,
8. probability of fiber breakage,
9. compression strength.

Some manufacturers are now providing cables designed to contain other conductors in the cable with the optical fibers. For example, twisted-pair wires can be included in the cable for use in other signaling applications, or to carry power to optical repeaters along the cable route. Figure 2-34 shows a complete cutaway sketch of one such cable. Two flat grooves on opposite sides of the dielectric member provide a "bed" for the optical fibers and the conducting carriers. A specific design contains up to six optical fibers that are laminated into a flat strip, and contained in one groove. The other groove carries up to three copper-wire pairs. In addition to the optical fibers or wire, a nylon tape can be used in the grooves for an added strength member.

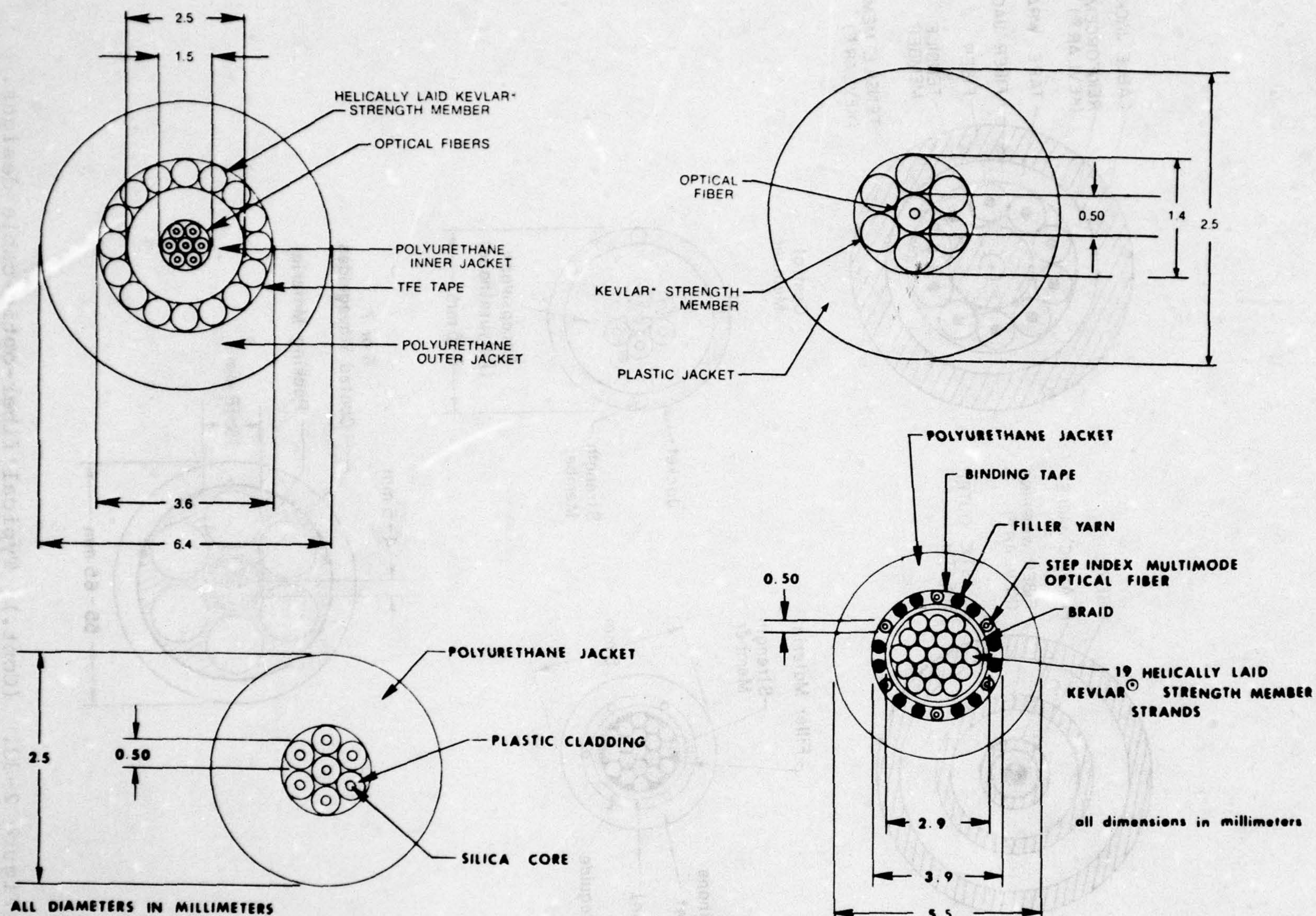


Figure 2-33. Typical fiber-optic cable designs.
Source: ITT Product Literature.

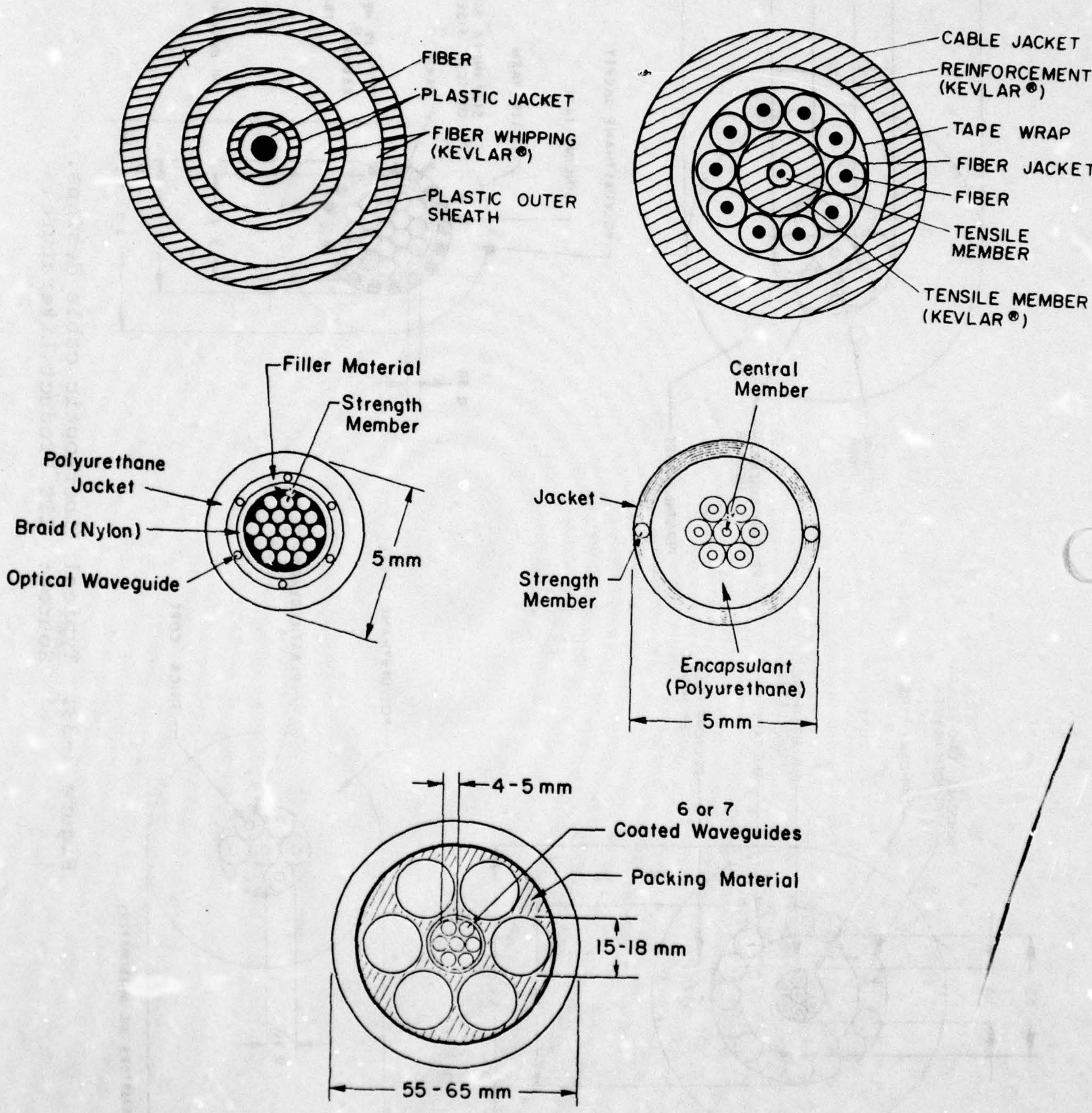


Figure 2-33. (Cont.) Typical fiber-optic cable designs.

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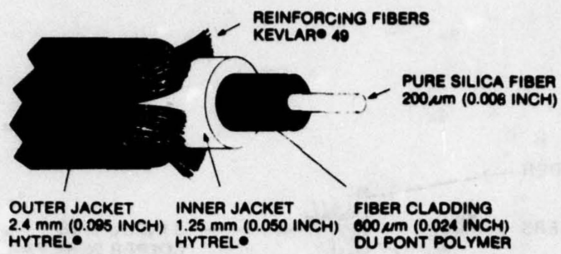
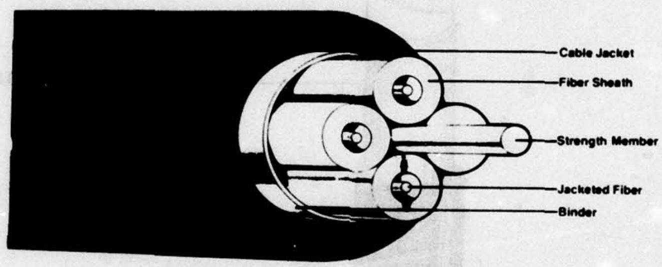
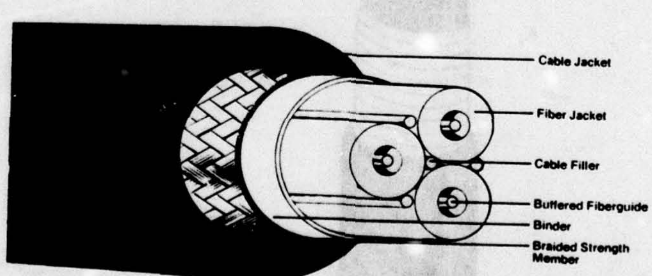


Source: Du Pont Product Literature.





Source: Times Wire & Cable Product Literature.

Figure 2-33. (Cont.) Typical fiber-optic cable designs.

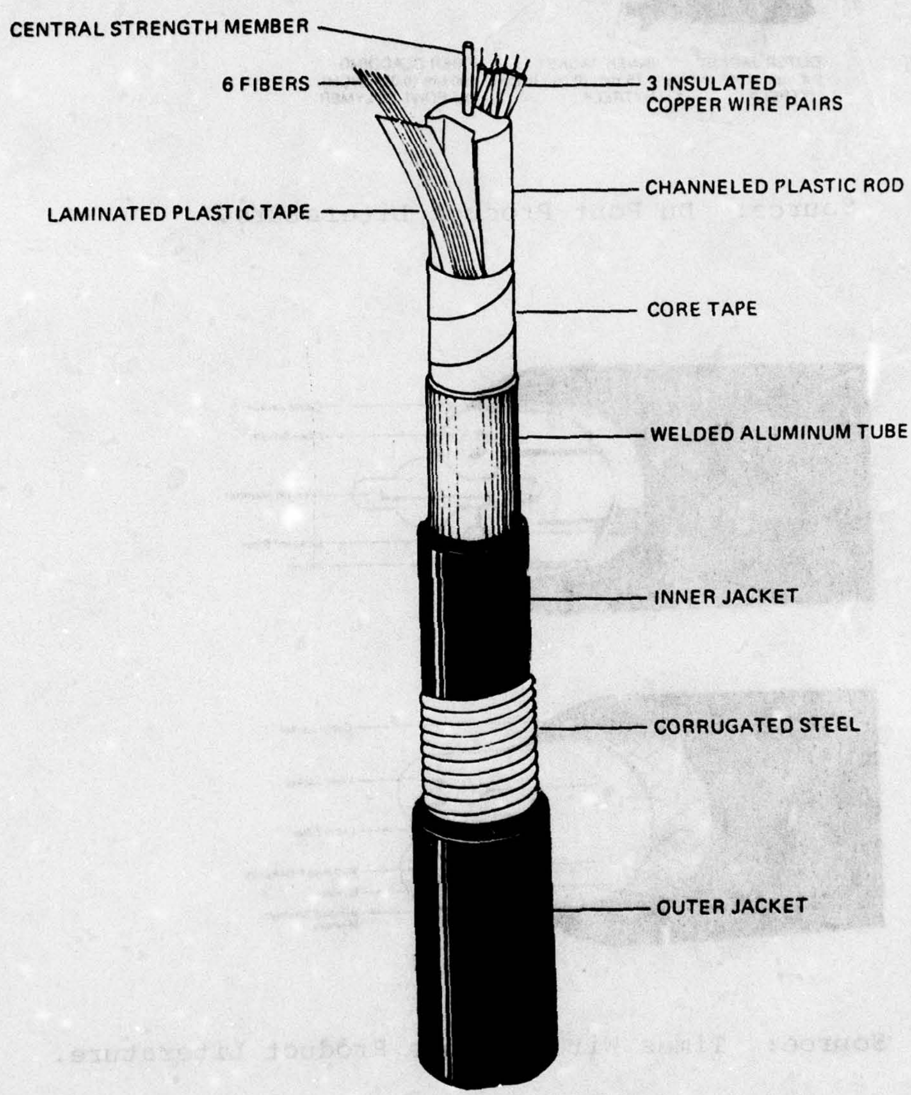


Figure 2-34. Cutaway drawing of a fiber-optic cable used in a commercial communication system (General Cable Corporation, 1977).

h. Fiber splices and Connectors.

Methods of splicing lengths of fiber to each other and terminating the ends in appropriate connectors constitute an important part of the design of an optical-fiber link. Both splices and terminations contribute a loss factor to the system budget and add a complexity to installation procedures.

The lack of standards in cable connectors is a problem for the designer, just as it is a problem in cable configuration; techniques for mating the fibers to the connectors vary a great deal, and the variety of cable size and configurations shown in the previous section serves to illustrate a problem in connector shell design. The trend at this time appears to be that individual cable manufacturers are designing and fabricating connectors for use with their specific cables. This situation limits the choice for the system designer. Some firms that have been active in the rf connector business are attempting to work closely with manufacturers of the fiber-optic cables, but have found that the latter change specifications so rapidly that it is difficult to fix even the outside dimensions of the connector shells (Makuch, 1977). However, recent product literature indicates that connectors for some of the popular cables are becoming available. A few examples of couplers for single fibers are presented later in the section to illustrate a variety of approaches. We do not attempt to cover the subject of complete cable connectors (with multiple fibers), except to illustrate current solutions to this problem.

Before we discuss the fiber connectors, a brief discussion of fiber splicing is in order. We distinguish a splice from a connector by the simple definition that a splice is intended to be a permanent connection, and a connector is intended to provide a convenient connect/disconnect operation. Splicing of optical fibers is not a simple process. Care must be taken in handling the fibers as they are very small and easily broken when unsupported or protected only by their jackets. Preparation of the end surfaces of the fibers is an important part of the splicing process; the ends should be as optically flat as possible. This

reduces Fresnel reflections and optimizes light transfer across the splice. Laboratory techniques of grinding and polishing the end surfaces are not practical solutions for field splices. Alternative techniques have been developed with good success. They usually involve a scoring process (with a diamond tool), followed by a method for fracturing the fiber at the line of the score. It has been found that this technique is applicable to field installation, and provides reasonable surface fractures and a small range of loss. The process needs to be carried out in such a way as to avoid any contaminating materials such as dust on the fiber ends.

After the fracture is made, the ends of the two fibers are brought into proximity of one another using a suitable guide, and joined with an adhesive or epoxy material. The latter is generally one that provides a good refractive-index match to the fiber. One typical method in which a precision glass sleeve is used as the guide for the fibers is sketched in Figure 2-35.

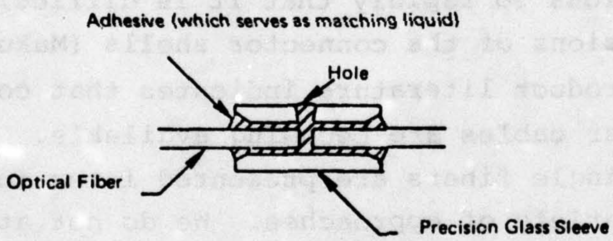


Figure 2-35. A typical sleeve-type fiber splice.

Obviously, after the splice is made as shown in the figure, the sleeve must be mounted in some sort of protective jacket or tube that provides lateral strength. A crimping technique can be applied to the fiber jacket if care is taken not to damage the fiber.

Another example of a splicing jig is shown in Figure 2-36. A single vee-groove guide is used to align the fiber ends as illustrated in the figure, and the splice is completed with epoxy material. Again an appropriate sleeve for protection and strength must be added to the completed splice. A very practical appli-

cation of this technique was recently used in the installation of a fiber-optics transmission system (Dworak, 1977). The vee-groove guide was formed from sheet copper material (rather than the block jig as shown in Figure 2-36). After the splice was completed, the guide was seated in a splint made of aluminum that contained a depression to seat the vee-groove guide. The splint was then covered with shrink tubing to complete the splice. The vee-groove guide became a physical part of the finished splice.

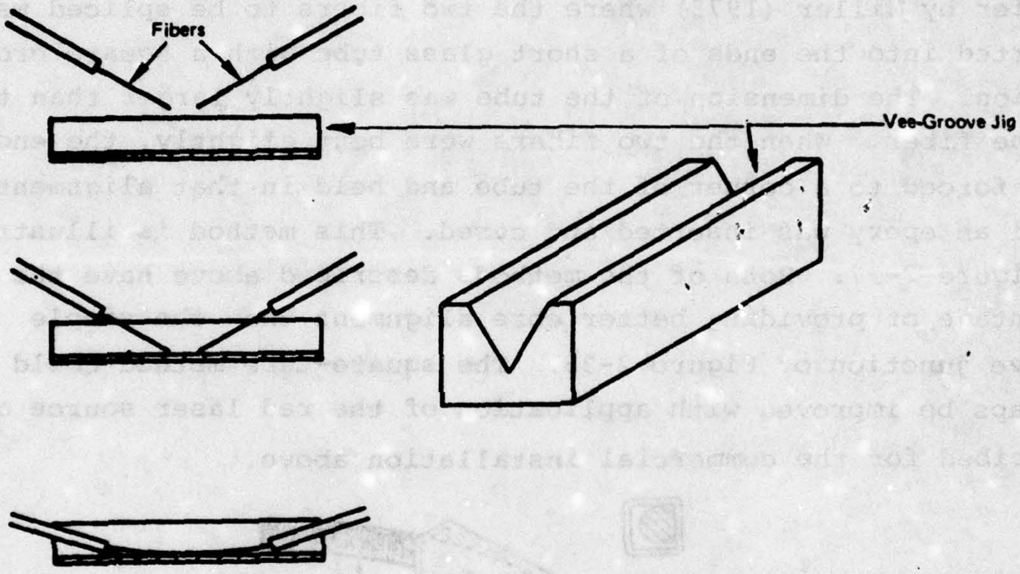


Figure 2-36. A fiber splice technique using a vee-groove guide.

A splice kit (containing the scoring and fracture tool and other aides to hold the fibers) was assembled for the field use. Experience gained in using this technique supplied the following significant data:

1. time required for a single splice was ~20 min.,
2. a total of 84 multiple fiber splices were made in the installation,
3. 75% of the completed splices were found to have losses less than 0.5 dB.

To accomplish these results, fiber alignment was aided with the field use of a laser in the visable red spectrum. The source was installed at the opposite end of the fiber from the splice to be made, and the technician aligned the fibers within the vee-groove guide so that visible emission was extinguished at the junction.

The technique employing the vee-groove guide was first reported by Kunze et al., (1976). A similar method was reported earlier by Miller (1975) where the two fibers to be spliced were inserted into the ends of a short glass tube with a square cross section. The dimension of the tube was slightly larger than that of the fiber. When the two fibers were bent slightly, the ends were forced to a corner of the tube and held in that alignment until an epoxy was inserted and cured. This method is illustrated in Figure 2-37. Both of the methods described above have the advantage of providing better core alignment than the simple sleeve junction of Figure 2-35. The square-tube method could perhaps be improved with application of the red laser source as described for the commercial installation above.

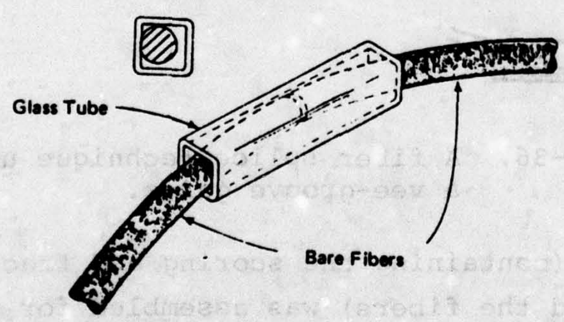


Figure 2-37. Sketch of a loose-tube fiber splice.

Fiber bonding methods other than the epoxy-adhesives methods have been used. They include resistance heating, electric-arc welding, and laser welding. The primary problem experienced using these methods has been the movement of fiber ends during the welding. High temperatures are required to assure adequate flow of material so that a strong weld will be produced, and

this induces movement in the fibers. The laser weld has been successfully used on silica fibers (Fujita et al., 1976). Resistance heating does not produce adequate heat for silica fibers, but it has been effective for compound glass fibers (Dyott et al., 1972).

The requirements for a fiber connector are much the same as those for a splice, with the added complexity that the connection must be made and broken repeatedly without damage to the fiber or fiber ends. Because of this requirement, index matching fluids cannot generally be used. There are two basic mechanical requirements that should be met in any connector:

1. reference surfaces for both the longitudinal spacing and lateral alignment should be provided, and
2. protection should be provided for the fiber ends against abrasion and the accumulation of contaminating particles.

The optical transmission objectives are simple: (1) to keep the loss through the connector as low as possible, and (2) to maintain modes in the transition from one fiber to the other. The latter is important for two reasons (and also applies to fiber splices):

1. the loss of modes contributes to lower coupling efficiency, and
2. a change in mode structure contributes to dispersion characteristics.

CHAPTER 3

OPTICAL MODULATION AND MULTIPLEX

3-1. INTRODUCTION

Modulation of an optical carrier for a communications system is an important consideration in system design. The options for the modulation method are somewhat restricted when compared to microwave systems, a fact that will become clear in this discussion.

It is perhaps coincidence (but a fortunate one) that the trend in communications today is toward all-digital systems, since optical-fiber communications is much more adaptable to digital (or discrete pulse-amplitude) modulation than it is to analog-signal formats. It is the purpose of this section to investigate the possibilities and the practical means for modulating the optical carrier in an optical-fiber transmission system.

Two general modes of modulation are possible, which we will classify as external and internal with reference to the optical driving source. External modulation (as the name implies) is accomplished in a separate device external to the carrier source. Internal modulation implies no additional component in the optical signal path, and the modulation is accomplished directly on the emission of the source driving the fiber. External modulation methods are not too practical within the context of the stated objectives and scope of this handbook, nor are they too practical in relation to the driving sources that we have considered in Chapter 2. On the other hand, we have called attention to new developments in laser sources that will no doubt become more viable at some time in the future. These developments will expand the options available to the designer. The laser sources in this class (solid-state and gas) will generally require an external modulator. Thus, for completeness, we will include some brief remarks about external modulation.

Internal modulation is limited to that of intensity modulation, as this is an inherent characteristic of the driving sources and

detectors discussed in Chapter 2. Both the LED and the LD sources are capable of direct internal modulation in the form of intensity modulation (IM), which is similar to the familiar amplitude modulation (AM) method used at lower frequencies. There is one basic difference between IM and AM, however, that should be kept in mind. In AM the modulating signal causes a linear change in voltage or current. In IM for the optical source, the modulating signal causes a linear change in the power output of the device.

Limiting our discussion of internal methods to the analog scheme of intensity modulation may (at this point) appear incongruous with our introductory remark that the optical fiber system is ideal for digital communications. However, we shall see that the devices are often capable of being switched on and off at high speeds, commensurate with digital signaling rates.

3-2. EXTERNAL MODULATORS

As noted above, the reason that external modulators are mentioned at all in this document is for completeness and possible *future reference. The use of some solid-state and gas lasers* will require this type of modulation.

An external modulator is a device that is inserted into the optical path following the driving source. The device operates on the optical signal in accord with the modulating signal. There are a variety of devices available commercially, but demand is so small that costs are high and the devices generally require high power consumption. Two techniques that are probably the most advanced are acousto-optic devices and electromechanical types.

The acousto-optic modulator is based on the interaction of the optical wave with that of a surface acoustical wave. The technology is related to that being developed in the surface acoustic wave (SAW) devices for other applications, such as tapped delay lines and matched filters at microwave frequencies. These devices provide intensity modulation of the light source. Their primary advantage in the optical-modulator role is the

relative ease with which they can be matched to rf drive sources and amplifiers, because of the transducers used.

The electromechanical type modulators, as the name implies, usually depend on some mechanical device to accomplish the modulation function - a rotating prism or mirror, for example. As might be expected, the response of such devices is relatively slow. As a part of this class, however, electro-optic devices have also been developed which employ a crystalline material. They are capable of much higher modulation rates than the mechanical types. Electro-optic modulators have been fabricated to produce three distinct forms of modulation, i.e., polarization, frequency, and intensity. Within our current framework of optical-fiber systems we are only concerned with intensity modulation, as the detectors we have considered are limited to this form.

As a general reference to these devices we cite Ross (1975). For our purposes, we summarize and conclude our discussion with the following general statements:

1. Electromechanical modulators are useful only for relatively low modulating frequencies.
2. Acousto-optic modulators can be used for modulating frequencies up to about 30 MHz, and are generally easier to use than other external types.
3. Electro-optic devices are operable for modulating frequencies up to and above 200 MHz.
4. There are few devices available for the fiber optical range of 0.8 to 0.9 μm wavelengths.

3-3. MULTIPLEXING OPTICAL CARRIERS

There are a few multiplexing techniques available to the system designer that can be directly applied to the optical carrier domain. We mention these briefly here as many of the modulation methods discussed in the balance of this section may be commonly applied to the multiplex forms.

The first technique we consider is almost elementary with respect to the optical cable. We have seen in Chapter 2 that many cables are fabricated with a number of individual fibers. This permits the use of independent sources and detectors on each fiber. The mechanism has been referred to as space division multiplex (SDM) by some authors. Although elementary, we show in Chapter 4 that this form of multiplexing has a very definite application for existing communication systems.

A very practical optical driving source for an SDM system was recently presented by Crow, et al., (1977). This device is a multilaser source which uses a silicon substrate for both the laser array and the optical components. Individual laser drive electrodes are provided, and isolated by reversed biased p-n junctions. A sketch of the source is shown in Figure 3-1. A thermoelectric cooling technique is incorporated into the package to maintain laser junction temperatures less than 30°C. The authors state that the theory and performance measurements confirm that this package can be operated with cw laser output power on the order of 10 mW when operated on a silicon heat sink. This particular source appears to be ideally suited to one of the communication systems discussed in Chapter 4.

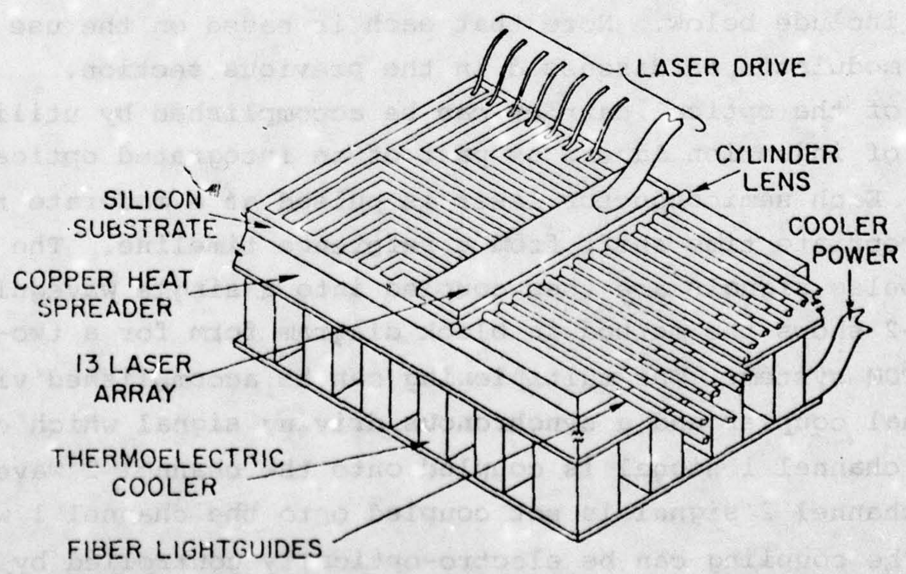


Figure 3-1. Sketch of a multichannel GaAs laser source (Crow, et al., 1977).

A second multiplex possibility is accomplished by using several optical sources, each one modulated with a distinct information signal. The sources would be chosen such that each one emits a distinctive wavelength and is coupled to a common transmission fiber. This process is known as wavelength-division multiplex (WDM). The technique is attractive in the sense that it can conceivably increase transmission efficiencies. For example, the state of the art in fiber systems today does not generally exploit the bandwidth capabilites, particularly in short-haul applications. The WDM technique is complicated to implement, however, since the process would require filters at the receiver (and possibly at the source) to isolate adequately the multiplexed carriers. The methods for launching the individual carriers into the fiber (either bundle or single) also complicates the process. Gallawa (1976) has considered these problems and concluded that WDM has some attractive features, but it may be only a distant possibility. A discussion of the filter techniques applicable to WDM is included in this reference.

The third and final multiplex technique we wish to consider is time-division multiplexing (TDM) at the optical carrier frequency. Gallawa (1976) has outlined two possible techniques which we include below. Note that each is based on the use of an external modulator as discussed in the previous section.

TDM of the optical carrier can be accomplished by utilizing an array of injection lasers as part of an integrated optical circuit. Each semiconductor laser is pulsed at a moderate rate with appropriate time shift from a reference timeline. The various pulse signals are then coupled into a single waveguide. Figure 3-2 shows the method in block diagram form for a two-channel TDM system. The multiplexing can be accomplished via a directional coupler and a synchronous driving signal which ensures that the channel 1 signal is coupled onto the channel 2 waveguide, but the channel 2 signal is not coupled onto the channel 1 waveguide. The coupling can be electro-optically controlled by applying an electric field which is synchronized in time to the

input signals. The electric field modifies the coupling mechanism by causing the two isolated waveguides to have unequal propagation constants when the electric field is applied. The length of the interaction region must be chosen such that the light entering one channel emerges from the other. The phase match required to accomplish coupling is switched on and off through the applied electric field.

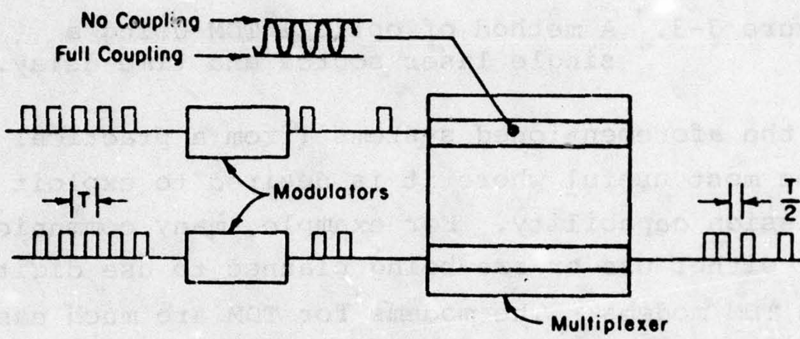


Figure 3-2. A method of optical TDM using a directional coupler and a synchronous driving signal.

Alternatively, a single laser can be used in conjunction with optical delay devices, as shown in Figure 3-3. If narrow pulses can be generated (short with respect to the repetition rate), the system bandwidth can be exploited by utilizing TDM. In using the technique shown in Figure 3-3, alternate paths contain optical delays between the various pulse trains. This shifts each pulse train in time so it can be modulated separately; the various pulse trains are finally recombined into a single, more densely populated pulse train. In theory, if the pulse width is 0.05 of the pulse spacing, the pulse train could be split into 20 separate pulse trains (channels). In practice, timing errors preclude such density; in such a case, perhaps 10 or 12 separate channels might be multiplexed with acceptable synchronizing errors.

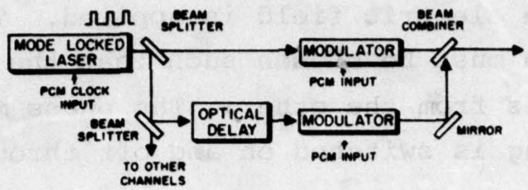


Figure 3-3. A method of optical TDM using a single laser source and time delay.

Both of the aforementioned systems (from a practical viewpoint) will be most useful where it is desired to exploit the fiber transmission capability. For example, many communication systems today either use or are being planned to use digital signaling and TDM modems. The modems for TDM are much easier to implement electronically than in the optical realm depicted in Figures 3-2 and 3-3. However, most current TDM systems, or other digital data-stream generators, do not tax the bit-rate capabilities of the fiber-optic medium. Thus, there is an application for such TDM schemes as those above, to exploit the transmission rate in optical fibers. In this view, we think of the two data streams shown in Figure 3-2 as emanating from two (or more) independent TDM systems (or other high-speed electronic data generators), and the optical TDM system is used to increase the overall transmission rate in the optical fiber.

3-4. INTERNAL MODULATION

The optical frequency as an information carrier can be modulated in any of three basic methods; namely, amplitude (AM), frequency (FM), or phase (PM). However, the latter two forms require external modulators, as pointed out in the previous section. Since we are concerned with fiber-optic systems, and the sources and detectors discussed in Chapter 2, amplitude (or intensity) modulation is the only form we will consider. The driving sources (both the LED and LD) can be conveniently

modulated internally in the intensity mode. The detectors (PD and APD) each respond directly to intensity modulation, producing a photo current proportional to the incident light intensity.

This limitation on modulation mode for the fiber-optic system is not as restrictive in overall application or design as it might first appear. We will find that there are many signaling formats that are very adaptable to intensity modulation. In fact, since intensity modulation has already been defined as the mode used for establishing the information carrier on the fiber, our discussion from this point will be concerned with the information signal (or the baseband signal). This signal may also be a modulated signal, and any modulation form discussed below will apply to the baseband signal only and not to the optical carrier.

It will be helpful in this discussion to keep in mind a few basic features of the optical frequency range as it is compared with the lower microwave bands:

1. The optical carrier is at a much higher frequency.
2. The coherence bandwidth of the transmission is much wider than at the microwave frequencies.
3. Response times of the components are inherently much faster than their microwave counterparts.
4. Optical fiber systems have poorer linearity characteristics.

Most of the signaling methods that can be applied with intensity modulation will be hybrid in nature for analog communication systems, and direct for digital transmission forms. Before considering these, however, it will be beneficial to review the key features of intensity modulation for the semiconductor sources introduced in Chapter 2.

a. Modulation of a Semiconductor Optical Source

The fundamental method of intensity modulating a semiconductor optical source (both the LED and LD) has been noted several times.

Some details regarding the quiescent operating point for intensity modulation were presented in Chapter 2. We will briefly review these points as follows:

1. The intensity of the driving source is varied directly with the bias current, in either the spontaneous emission region (LED) or the lasing region (LD) (see, for example, Figure 2-12).
2. For continuous analog modulation, the quiescent bias current must be established at a point such that the modulating signal causes an equal plus and minus swing about the quiescent value, and in the most linear range of the intensity characteristic.
3. For most digital modulation or pulse forms of analog modulation, the quiescent bias current is adjusted for the driving sources as:

   LED - either near zero or at a quiescent point optimum for noise and/or speed requirements.

   LD - at a point near (but below) threshold if threshold transition noise is tolerable.
   - slightly above threshold if transition noise must be reduced.
   - near zero if transition speed is adequate for the signaling rate, and threshold transition noise is tolerable.
4. For continuous analog modulation of an LD, care must be taken to consider the life of the source when operating in the continuous laser mode at a bias much above threshold. An LD for this application is designated as a cw laser.

3-5. SIGNALING METHODS FOR OPTICAL FIBER SYSTEMS

The baseband or information carrying signal for an optical fiber system can be of many forms, both analog and digital. Most of the familiar forms can be accommodated by the intensity modulation capability of the optical source and detector. In this

section, we will define the baseband signals of interest, and discuss their fundamental features for communications. As noted before, if the baseband signal itself is a modulated signal, the transmission signal is hybrid. This will be the case for a number of analog communication methods. In addition, it may be expedient to change the basic signal format to some other form before transmission.

a. Analog Signals

There are two distinct forms of analog modulation; continuous and pulse forms. The distinction between an analog signal and a digital signal should not be confused relative to a pulse format. A continuous analog signal is one which can take on any value (within high and low limits) and is transmitted accordingly. A pulse form of analog signal can also take on any value, and is merely a sampled form of the continuous signal.

The modulation forms for a continuous analog signal are well known as:

1. AM (amplitude modulation): the carrier amplitude is caused to vary continuously with the magnitude of the modulating signal.
2. FM (frequency modulation): the frequency of the carrier is caused to vary continuously with the magnitude of the modulating signal.
3. PM (phase modulation): the phase of the carrier is caused to vary with the magnitude of the modulating signal.

The first form above is directly applicable to the fiber-optic system, as a continuous signal can cause the intensity of the source to change. However, the other two are only applicable when used to modulate a subcarrier frequency (lower than the optical carrier). The subcarrier in turn is used for intensity modulation of the optical source. It was pointed out in Chapter 2 that the optical sources are inherently non-linear; thus, any form of continuous analog modulation will suffer distortion. The

net distortion for the subcarrier FM and PM modes may not be as severe as for direct AM, since they are by definition also non-linear. Any of these forms should only be applied where the non-linear distortions can be tolerated.

Pulse forms of analog modulation can be accomplished in a variety of ways. Each one is based on the sampling theorem, where the continuous signal is sampled at an appropriate rate and the information in the signal is completely retained in the periodic sample values. It should be emphasized that the sample values are permitted to have (proportionally) the same range of magnitude that the continuous signal has; thus, it is a continuous analog signal in pulse form. The variations of this signal format are defined as:

1. PAM (pulse amplitude modulation): a periodic pulse train is generated such that the amplitude of each pulse is proportional to the magnitude of the continuous signal at the time of sampling.
2. PDM (pulse duration modulation): a periodic pulse train (generally of equal amplitude) is formed where each pulse in time is proportional to the sampled value of the continuous signal.
3. PPM (pulse position modulation): a periodic pulse train of equal width is formed such that the position of the pulse in time relative to its predecessor is made to vary proportionally to the amplitude of the sampled value.
4. PRM (pulse rate modulation): a pulse train is formed, composed of many short duration pulses for each analog sample, and the repetition rate of these is caused to vary proportionally to the sampled value.

Examination of the definitions for these pulse-analog forms will indicate that they are variations of the three basic analog methods. For example, they all vary either the magnitude (amplitude or width), frequency (rate) or phase (position) of the

representative pulse train. The advantages of the pulse-analog forms with respect to optical-fiber systems will be noted in our later discussion of digital modulation.

Each of the above signals is a modulated signal by definition, since some parameter of the pulse train is being varied in accordance with the original analog signal. However, the sampling rate is generally low (1/2B for the sampling theorem, where B is the bandwidth of the information signal). Thus, the fundamental of the pulse repetition frequency is not much higher than that of the modulating signal, and the composite signal forms only the baseband of a transmission system. In other words, these signal formats must still be applied to a high-frequency carrier for final modulation and transmission. In the fiber-optic system, they will serve to modulate the optical carrier in the intensity mode in much the same manner as the digital signal formats (see Section 3-6).

In formulating the pulse-analog signals the original sampling process forms the basic PAM. Other pulse forms are generally derived from the PAM signal in conversion processes.

b. <u>Digital Signals</u>

Digital signals are defined as those that are permitted to take on only discrete values over a specified continuous range. They are derived generally as the pulse-analog signals are, i.e., from sampled values of a continuous signal. However, the samples are restricted to assuming the nearest discrete level of those specified within the signal range. In the sampling process, the difference between a PAM signal and its digital counterpart is that the PAM amplitude may have any value while the digitally sampled signal may only have discrete values. Obviously, the latter is a special case of PAM, known as digital DPAM.

The digital process generally continues from the DPAM signal, and codes the discrete values in some manner. For example, if we choose a binary system of 0's and 1's as the only allowable states, and if we code each discrete level into a binary number, the result is referred to as pulse code modulation (PCM). PCM is

the most common form of digital signaling. A variation on PCM that is frequently encountered in communication systems is known as delta modulation (ΔM). The basic difference between the two forms is the method of coding the samples. The ΔM system codes the difference between successive samples rather than the sample size itself as in straight PCM. There are variations also within the ΔM technique, but these are beyond our scope.

The number of discrete values selected for a PCM signal determines the number of binary bits required to represent each level. For example, if we select $2^n = 64$ discrete levels in a binary system, then $n = 6$, and we require 6 bits of information to represent any one of the 64 levels. In such a coding process we note that one amplitude sample requires n times as many pulses to convey the magnitude of the sample in a PCM format. Thus, we pay a penalty in speed or bandwidth required, but this penalty is usually compensated for in terms of performance and/or convenience.

There are obviously other forms than the binary form of coding a DPAM signal. We could allow three or four discrete levels in place of the binary system. Such coding is beyond the scope of this report. However, we will note in Chapter 4, a case of a particular communication system in which three levels of coded information are transmitted.

From the definition of a digital signal, it can be seen that other pulse analog forms could be restricted to a finite number of values to form a digital counterpart. In addition, each of these may also be coded and transmitted in a PCM format.

There are both advantages and disadvantages of a digital signal format compared to its analog counterpart. The first advantage is that the digital forms can be coded as noted above, resulting in a pulse train with only two levels (binary coding). The detection process for a PCM signal is greatly simplified, since the receiver need only decide whether a pulse at any given instant of time is present (binary 1) or absent (binary 0). This provides a high immunity to noise in the system, compared to uncoded formats where the receiver must detect either an

amplitude level or a time parameter of the received pulse. Additive noise and jitter in such a system can easily contaminate the signal causing the receiver to yield a false detected value.

The significant advantage of pulse code signals is that after detection, they may be regenerated in their original form for retransmission. This feature is very attractive for communication systems requiring repeaters. An analog signal suffers distortion and noise contamination in each segment of a link with repeaters, and the effect is compounded in each segment. The digital coded signal after regeneration can be equivalent to the original signal, and the effects of each link segment are not compounded. Digital coded signals are also easy to transmit. The biggest disadvantage is the increased bandwidth required to convey the same information. Thus, the information rate of a coded digital channel is lower than that for the analog channel. Further considerations on performance parameters and information capacities are subjects that belong in information theory. In this document, we will only be concerned with the bit-error-rate (BER) performance of a digital coded system in transmission from point to point.

3-6. TRANSMISSION METHODS IN THE OPTICAL FIBER

Section 3-5 presented an outline of the various forms of both analog and digital information signals that can be used in an optical-fiber system. In this section we will discuss the transmission modes for these signals on an optical-fiber waveguide, or the final process for intensity modulating the optical carrier. Single channel signals and/or fibers will be the only configurations discussed in this section. Multiple channel systems involving both FDM and TDM transmission schemes will be discussed in Chapter 4.

Rather than classify the transmission methods on the basis of whether the baseband signal is analog or digital, we choose a classification based on whether it is a continuous analog signal or a pulsed form. This differentiation lends itself to the

intensity mode of modulating the optical source, as any pulse form of a baseband signal will be applied in essentially the same manner whether it is analog or digital.

a. Continuous Analog Transmission

This transmission method is the most straightforward, and has been mentioned several times in other sections of this document. The continuous analog signal is applied directly to a circuit designed to vary the reverse-bias current of the optical driving source. The quiescent driving point is selected in accordance with the points made in Section 3-4. The modulating signal must vary about the quiescent point over the most linear range of the intensity characteristic, and must be limited in its magnitude to avoid driving the optical source into threshold boundary or overload conditions. Linearity is a problem in this transmission mode, however, primarily due to the driving source characteristic. The method has been demonstrated for such wide-band signals as television, but limited to relatively short transmission distances. The method may be viable for other analog signals where the nonlinear effects are less important.

The most useful form of continuous analog transmission is in the hybrid area, where the baseband signal is a modulated sub-carrier. The subcarrier may contain the information signal in any of the continuous analog forms of AM, FM or PM. It would be applied as the continuous signal to the intensity-modulation driver circuit. The first design consideration for using the subcarrier technique is to assure that the subcarrier frequency is low enough to be within the speed capabilities of the source and detector, and that the overall BW of the subcarrier signal is within the length-bandwidth product limit of the selected fiber. Another important consideration for the FM and PM signals is dispersion in the fiber transmission. Total dispersion of the subcarrier frequency must be small compared to the variation in frequency or phase, respectively, caused by the modulating source.

Nonlinear effects of the optical-fiber system will have an impact on the hybrid transmission mode. Little work has been done, either theoretically or in the laboratory, to evaluate the seriousness of the problem, so that few references can be cited. One particular example of comparing the performance of a subcarrier mode with other transmission methods is presented later in this section (Fig. 3-9). The performance parameter chosen for the comparison is rms signal-to-noise ratio (SNR) as a function of optical received power.

The only general design guideline that can currently be cited for the hybrid techniques is relative to SNR. It is obvious that if this transmission mode is used, the optical driver is preceded by a communication system that develops the modulated subcarrier. In turn, the optical detector must be followed by a receiver system designed to perform the demodulation of the subcarrier signal. The design requirements are in terms of the required SNR for adequate performance of the base communication system. The designer of the optical system must then ensure that the optical components and fiber in concert do not degrade the available SNR at the transmitter end below that required at the communications receiver. Experience in application of these techniques is limited to the point that additional performance considerations cannot be delineated.

One general word can be added relative to nonlinear effects in subcarrier FM or PM techniques. These two modulation forms are themselves nonlinear (exponential), and it might be expected that the nonlinear effects of the fiber-optic system would be negligible in comparison. However, more investigation, both theoretical and experimental, is required to evaluate these effects.

Regardless of how carefully a classification of certain topics might be made, it frequently happens that there are some which will defy the classification and belong partially to more than one. Such is the case for the baseband signals known as frequency-shift-keying (FSK) and phase-shift-keying (PSK). Since

the transmission mode for these signals fits our definition of the continuous analog method, we include them here, even though it is obvious that the information signal is in the pulse code or digital format. These signals convey information by shifting frequency or phase in accord with two or more defined states in a coded pulse train. They are considered therefore as part of our subcarrier or hybrid transmission schemes for the optical fiber system.

Before concluding our discussion of the continuous analog transmission methods, a word about the design approach for these systems should be made. It will be found in Chapter 6 that the emphasis of the specific design procedures is on the digital communication system. This is considered to be proper in the light of today's trend, and will fulfill the greatest percentage of need for the optical system designer. However, in Chapter 4 we discuss a particular communication system that has been in use for many years, and is quite familiar to the microwave engineer. This is the FDM multiple-channel communication system that forms the backbone of current military networks (FM/FDM). These systems are likely to be in operation for some years before they are completely supplanted with digital techniques. Therefore, design procedures for adapting the FM/FDM system to an optical-fiber transmission link could also be important. Specific details for this configuration are presented in Chapter 4. At this point, we wish to augment the procedures given in Chapter 6 for the continuous analog methods in general.

Essentially the design procedures for the continuous analog transmission methods are the same as those given in Chapter 6, and will follow the same order of events as presented for the digital transmission mode. Two exceptions, however, are noted. First, the dispersion problem will not be as important to the analog methods, and need only be considered relative to the sub-carrier or high-frequency components contained in the baseband signal as noted previously. Second, the required performance will be based on SNR rather than on the BER performance measure

as used in Chapter 6. It is this latter information which we will augment here.

One of the first design steps necessary is to identify the required performance criteria, and from this specification, to determine the optical power necessary at the detector of the fiber-transmission system to meet the required performance. The required SNR value is thus the criterion for the analog method. Absolute values of SNR for the particular baseband signal will depend on the communication system being used, i.e., if a hybrid method is involved. For the fundamental requirement over the optical system, design guidelines can be presented.

The expressions presented in Section 2-4 can be used either to calculate the SNR for a given set of components, or more directly, the detector power can be calculated for a desired SNR. Parameters of the specific components (particularly those related to the detector, such as equivalent load) are necessary for use in the calculations. When these are known with sufficient certainty, equations such as (2-12) may also be used to determine optimum gain values for an APD detector in order to optimize the SNR at the detector output.

As a general guide to this design step for the analog transmission modes, state-of-the-art data for the optical receiver can be cited. By optical receiver, we mean the optical detector and an associated low-noise preamplifier circuit that is presumed to be well-matched to the detector and the signal BW. Typical characteristics (showing the average received power at the detector versus the signal BW) are shown in Figures 3-4 and 3-5 (ITT, 1977). Figure 3-4 presents the data for a typical PIN detector, and Figure 3-5 for a typical APD. In both figures, the parameter of the set is the SNR. These curves can be used in place of the similar data for BER performance given in Chapter 6. For specific detectors, however, either the calculation method above should be used, or similar data should be obtained directly from the manufacturer of the optical detector/receiver.

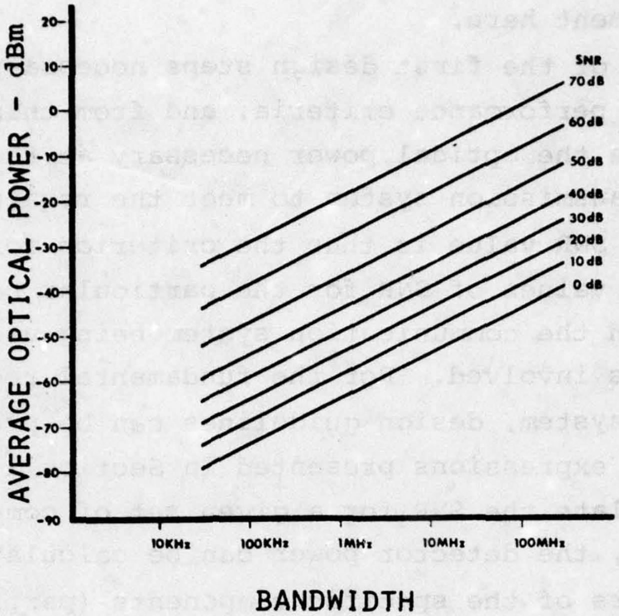


Figure 3-4. Required optical power vs. bandwidth for an analog receiver with a PIN detector (ITT, 1977).

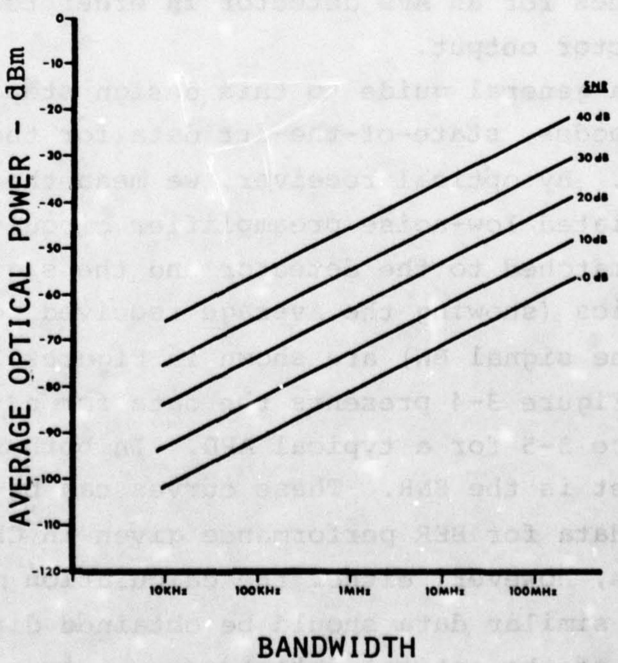


Figure 3-5. Required optical power vs. bandwidth for an analog receiver with an APD detector (ITT, 1977).

Another useful set of design curves has been developed by Wittke (1975), as shown in Figure 3-6. Here the SNR-BW product is plotted versus the optical power at the detector for typical PIN and APD detectors. The PIN characteristics are shown in the solid-line curves for current gain M = 1. The APD curves are those given in dashed-lines where M = 100. The parameter of each set is the equivalent load resistance R_{eq} as defined for Equation (2-5). These characteristics are derived from Equation (2-4) by multiplying each side of the expression by the bandwidth B. The other applicable values for the characteristics are noted on the figure, namely, for a modulation depth of unity (m = 1), an assumed excess noise factor F = 4(6 dB) and a responsivity R = 0.57 A/W for the PIN detector.

The expected modulation BW over a fiber-optic system can be gleaned from measurements presented by Wittke (1975). Figure 3-7 shows the measured response of two fairly typical low-loss fibers as a function of modulation frequency for a nominal length of 1 km. Note that both of these fibers had relatively small NA values, and thus fewer modes were supported.

The modulation characteristic for a fiber can be affected by the coupling conditions between the source and the fiber. Figure 3-8 illustrates this effect for a GI fiber 645 m long, where the half-angle of the incident light cone is the parameter in the curves. Data such as that shown in both Figures 3-7 and 3-8 must be taken only as "typical" since the coupling methods used in the measurements and the driving source characteristics can easily change the result for the same fiber and the same length. Actual data for any given fiber and associated driving source should be sought through manufacturers' literature.

At the beginning of this section, we made reference to some comparative data for a subcarrier transmission mode and other forms of transmission. These results are given in Figure 3-9, where three independent transmission modes have been compared over the same fiber and using a common detector. The three methods are identified in the figure; a subcarrier FM, a PPM and

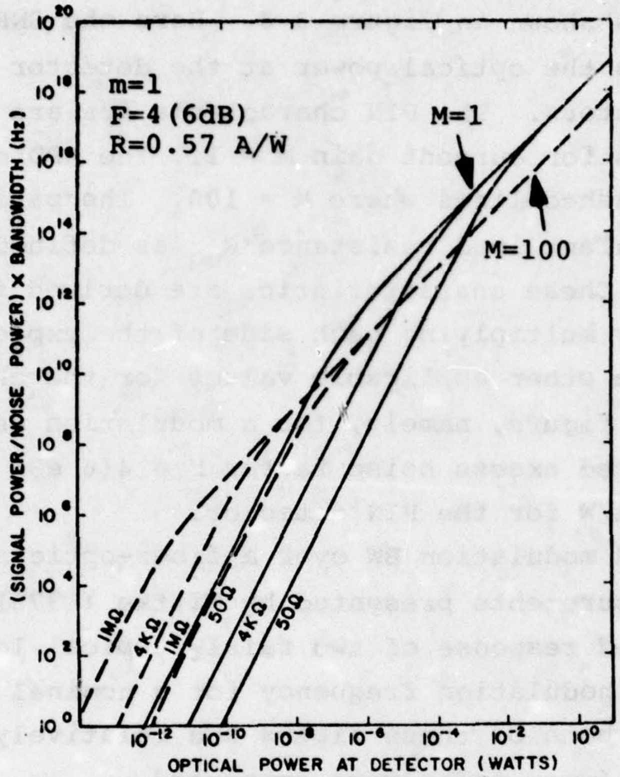


Figure 3-6. Typical SNR-BW product available for different detector gains and effective load resistance (Wittke, 1975).

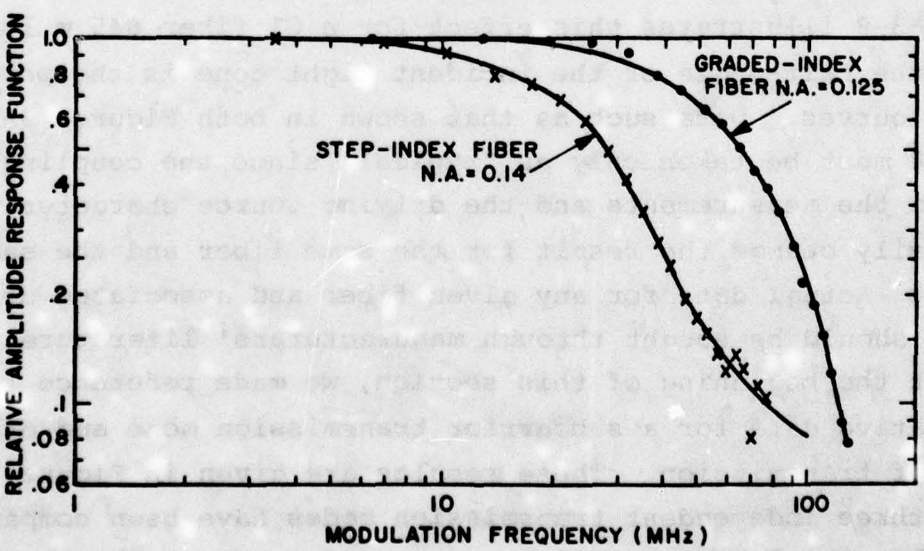


Figure 3-7. Modulation transfer characteristics for two typical low-loss fibers (1 km length) (Wittke, 1975).

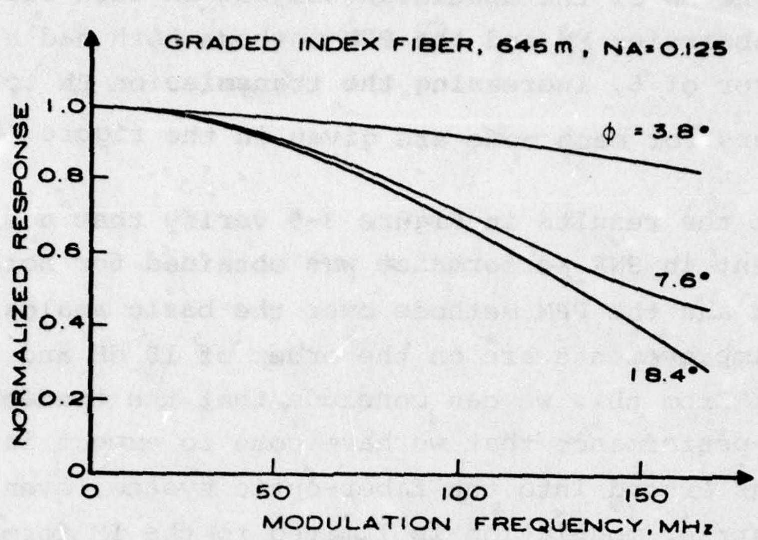


Figure 3-8. Modulation characteristics for a graded index fiber measured under different coupling conditions. ϕ is the half-angle of the incident light cone (Wittke, 1975).

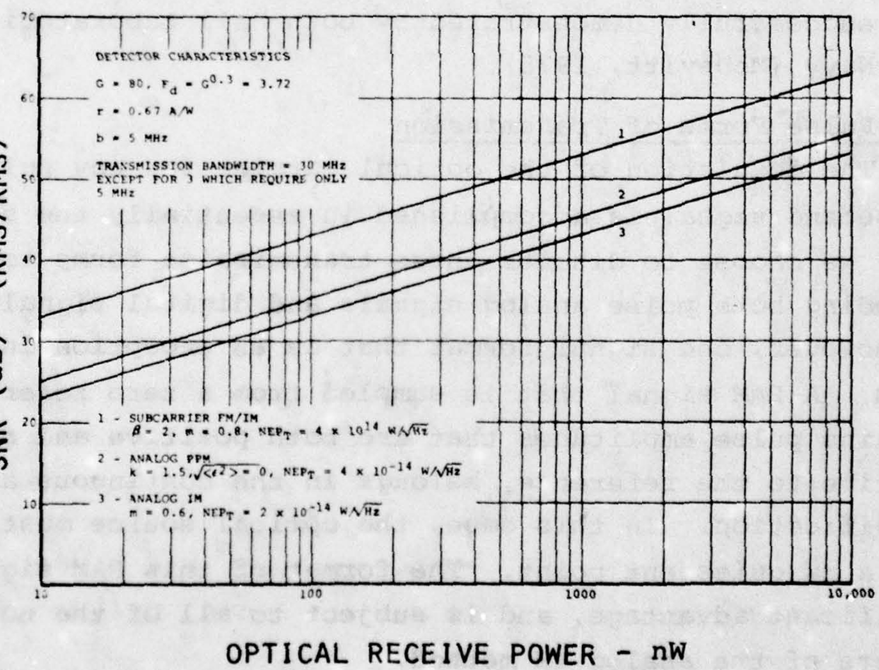


Figure 3-9. Comparison of received optical power required for a specified SNR for three different transmission methods (McDevitt, 1975).

a basic IM. The BW of the modulating signal in each case was 5 MHz. The subcarrier FM and the PPM methods both had a BW expansion factor of 6, increasing the transmission BW to 30 MHz. Other parameters for each mode are given in the figure (McDevitt, 1975).

Note that the results in Figure 3-9 verify that a significant improvement in SNR performance was obtained for both the sub-carrier FM and the PPM methods over the basic analog IM result. The improvements are on the order of 10 dB and 3 dB, respectively. From this we can conclude that the tradeoff in bandwidth and performance that we have come to expect in the microwave bands extend into the fiber-optic system, even though the optical carrier modulation is limited to the IM form.

Results such as these add credence to our earlier remarks regarding the practical application of baseband signals from existing communication systems to the fiber-optic waveguide. The subcarrier FM and analog PPM methods (as in Figure 3-9) have been successfully demonstrated by both Bell Laboratories and the U.S. Navy (McDevitt, 1975).

b. Pulse Forms of Transmission

The modulation of the optical carrier for any pulse form of a baseband signal is accomplished in essentially the same manner. Thus, we choose to discuss these transmission forms together; including both pulse analog signals and digital signals. There is, however, one signal format that is an exception in this class. A PAM signal that is sampled from a zero reference, and contains pulse amplitudes that are both positive and negative relative to the reference, belongs in the continuous analog classification. In this case, the optical source must be driven from a cw quiescent point. The format of this PAM signal has no significant advantage, and is subject to all of the nonlinear effects of the analog IM method.

Other forms of PAM whether analog or digital, are also subject to the nonlinearity problem in the fiber-optic system. For

this reason, the PAM signals are not considered optimum for direct transmission. We have already seen in the last section that the PPM format has a distinct advantage over the analog IM signal transmission, but requires a BW expansion. Some additional BW is required for any pulse signal form compared to its continuous counterpart however, so some penalty has already been paid in the PAM form. Thus, it is recommended that the PAM signal not be used directly in system designs, but be converted to an associated form such as PPM prior to transmission.

The actual modulation method used to intensity modulate the optical source for pulse signals has been discussed previously (see Section 3-4). The purpose of this section is to consider the various options and tradeoffs for the pulse signal forms. Emphasis will be placed on the digital signals such as PCM.

Using the modulation methods discussed in Section 3-4, any of the analog pulse forms can be conveniently transmitted over the optical fiber. A time multiplex scheme could conceivably be used with PAM, but the other forms (PPM, PDM, and PRM) all vary a time parameter of the pulse train. Thus, any form of TDM with these signals would be difficult to achieve, and with little advantage in comparison with a coded (or digital) signal. If it is desired to increase the transmission capacity in an optical fiber where a number of analog pulse signals form the baseband, an FDM technique could be used in a subcarrier mode. In this case, the pulse signals would necessarily be at a low pulse repetition rate. A second option would involve the optical carrier multiplex schemes discussed in Section 3-3.

As a general rule, when the designer of the optical-fiber system is faced with transmitting information in any of the analog pulse forms, he should weigh carefully the option of converting these signals to a pulse code form. The digital process offers a great many advantages in performance improvement, at the expense of transmission rate or BW. It is, however, also generally true that the pulse analog signal forms are derived from information signals of relatively small BW. In

these cases, conversion to a digital transmission signal does not require a significant BW penalty. The primary advantages would be:

1. increased efficiency in respect to the transmission capabilities of the optical link,
2. the option of TDM of a number of baseband information signals.

The balance of this section will be devoted to the digital form of pulse transmission. The performance requirements and parameters associated with digital signaling have been noted previously, and are treated comprehensively in Chapter 6 directly with the design procedures. Digital signaling will, no doubt, be the dominating baseband signal for design applications and proposal evaluations, and for this reason the design procedures have been presented to emphasize this transmission method. Our discussion here will be limited to the binary-coded system.

The one remaining design consideration for the digital signal is that of the actual signal format. The binary coded signal can be structured in a number of different ways. A few of the fundamental forms of interest are defined as:

1. NRZ (nonreturn to zero): in this form a binary logic "0" is usually designated by the absence of a pulse or by the lower limit of the two levels distinguishing the "0's" and "1's". An NRZ signal is structured in such a way that it remains at the logic "1" level for successive "1's" in the code; it only returns to the "0" level when this logic element occurs in the code chain. This format (by definition) results in having a single pulse (or bit) completely occupying the designated bit-time.
2. RZ (return to zero): in this form each pulse or bit representing a "1" returns to the zero level within a designated bit-time. Thus, the actual pulse within the chain must be less than a designated bit-time in width.

3. Bipolar NRZ: a signal structured the same as the NRZ above, with the distinction that a logic "1" is alternately reversed in polarity.

4. Bipolar RZ: a bipolar signal formed as the bipolar NRZ form above, with the exception that the signal always returns to zero within a bit-time. This form is frequently referred to as simply bipolar.

5. "Manchester Code": a signal format in which the information is carried by a change of state within a bit-time. A logic "0" is usually defined as a positive going transition, and a logic "1" as a negative going, transition. This signal can be unipolar or bipolar.

In the case of the two bipolar forms defined above, there is some confusion noted in the literature regarding definition. Those given above are found in some sources, and a different definition in others. The difficulty can be cleared with the following notes:

1. The above definitions are applicable when the signals are three-level binary (pseudoternary) i.e., where one of two source symbols is represented by alternating polarities and the other by a zero level.

2. The second definition found in the literature is applicable when the signal is strictly binary bipolar; i.e., when one source symbol is represented by one polarity and the other by the opposite polarity.

All of the above signal formats are illustrated in the sketches in Figure 3-10. There are many more possibilities and variations on these signals that will be found in the communications and information theory literature. Each will have some particular feature or parameter of prime advantage to the communication system in which it is used. However, these matters are beyond our scope and we leave them basically to the other disciplines. The reason for our interest is only in relation to

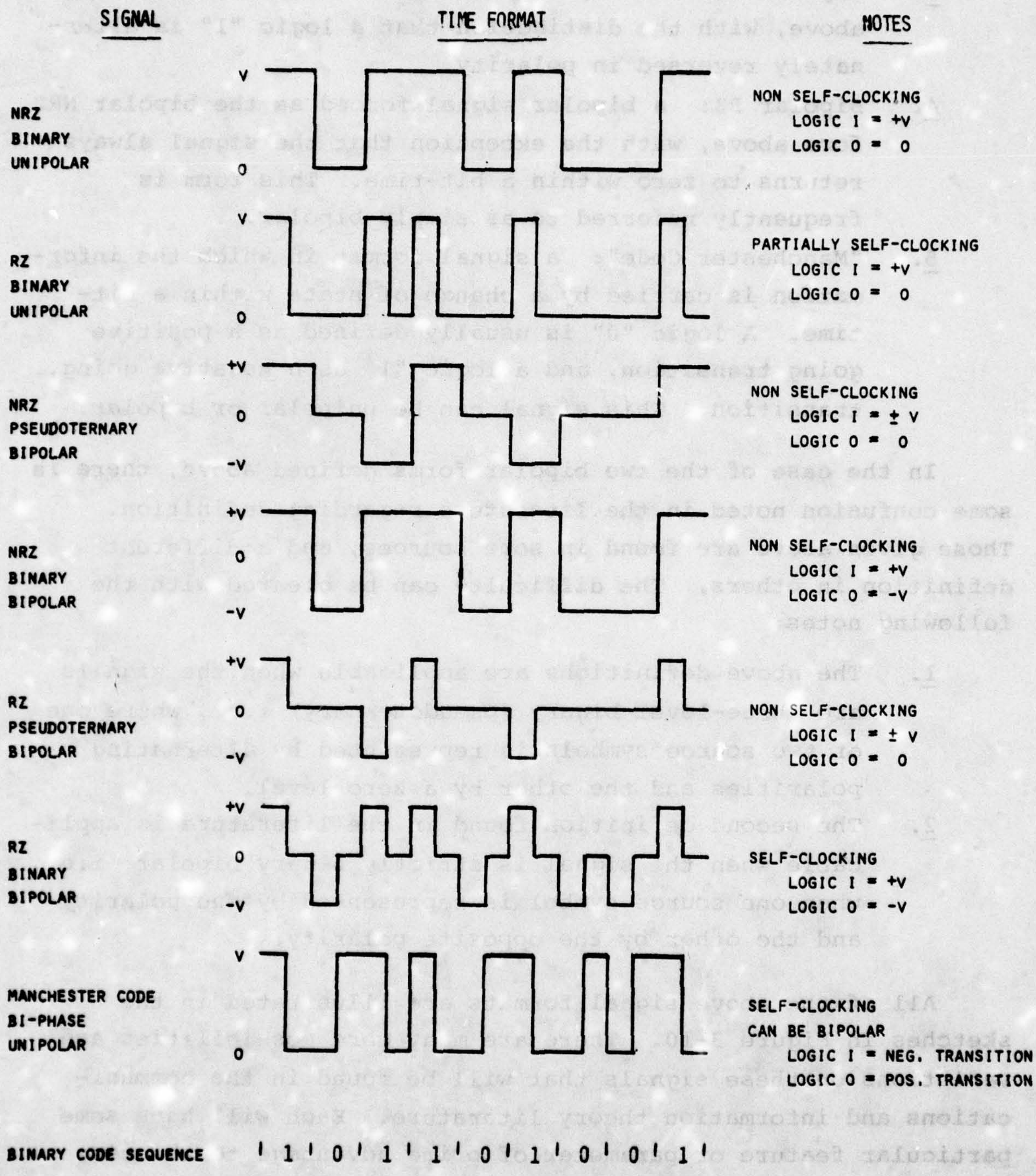


Figure 3-10. Examples of various pulse signal formats.

digital transmission over the optical fiber. The representative set of digital signals above is sufficient for our purposes.

There are five basic parameters of these digital signals that are of concern in adapting them to the fiber-optic transmission system. These are

1. Unipolar or bipolar.
2. Bit-time and/or rate.
3. Duty cycle.
4. Power and spectrum.
5. Clock information.

The question of using the unipolar or bipolar form is directly relevant to the internal intensity modulation of the optical source. We have already seen that the desirable mode for effecting this modulation is in the form of on-off keying (OOK), which does not require a cw quiescent point for either the LED or the LD source. For this reason, the unipolar signal form is preferable. However, for many communication systems, synchronous detection of the bit stream is required in the receiver. The basic clock rate of the transmitter modem is generally derived from the received pulse train to provide the synchronous clock for the receiver. The digital signal forms are thus classified as being self-clocking or nonself-clocking. The unipolar signals are not ideal for synchronous detection.

The structure for a completely self-clocking signal is such that there must be a transition in state during each bit interval (the basic clock rate). These transitions thus permit the receiver to recover the clock rate used at the transmitter terminal. A glance at the signals sketched in Figure 3-10 will indicate that the unipolar NRZ signal does not have this timing feature, and is therefore nonself-clocking. In addition, neither form of the bipolar NRZ signals is self-clocking. The unipolar RZ form is classified as being partly self-clocking, and this feature can be gleaned from the sketch of the signal. Any form of RZ signal will obviously contain more transitions in a given

interval than its NRZ counterpart. Note in the sketch of the unipolar RZ signal that the self-clocking transitions are present in a contiguous set of logic "1's", but not for a set of logic "0's". For this reason, the signal is only partially self-clocking, and the method used to recover the clock from the signal will depend on the code formulation and an integrating time. One form of the bipolar RZ (binary form) is seen to be a completely self-clocking signal.

The two factors discussed above (unipolar and self-clocking) illustrate the interest in such signals as the "Manchester Code" signal in Figure 3-10. This signal has both of the desired features: it is a unipolar signal for best adaptation to the optical LED or LD source, and by definition it has at least one transition of state in each bit interval. There are other similar "codes", such as the Miller code (Electromechanical Design, 1971), which have the same features.

For systems that do not require synchronous detection, the self-clocking feature of the digital signal is not important and the choice of format can be made based on other considerations. For synchronous systems, however, the optical transmission system must maintain the integrity of the signal, and choice of self-clocking formats are necessary. Some communication systems are designed to operate in either a synchronous or nonsynchronous mode. In such cases it may be found advantageous for the optical-fiber system to provide for a change in signal format. Details for such a change cannot be delineated without considering specific system requirements. We point this fact out as a design option that should be kept in mind, and used if an advantage in the optical transmission domain can be realized.

Also, some digital systems are specified to operate with either a unipolar or bipolar signal form. To accommodate these systems, it will generally be beneficial in designing the fiber-optic link to provide a signal conversion. For example, the unipolar signal may be permanently selected as the output from the transmitter modem (regardless of the operator selected mode)

and applied to the fiber-optic transmission system. A conversion to the appropriate bipolar signal form can then be made at the receiver terminal, when this signal form is selected by the operator.

The other parameters of interest (listed above) for the digital signal format are almost self-explanatory. The bit-rate is important to the fiber-optic design procedures as presented in Chapter 6. System performance, choice of fiber and other components, and the permissible length of the link will all depend on this parameter.

The power contained in the signal form is important, since we are dealing with a power modulating source and a power detector in the fiber-optic system. The power per information-bit should be as high as possible. From this standpoint, the NRZ signal forms are preferable, particularly for the LED driver. In the case of the LD, however, we can drive the source to high power levels for short intervals of time and conserve the life of the device. This aspect makes the RZ forms with short duty cycles the preferable choice. Spectrum or BW of the signal becomes more important in these cases, since the BW required for the signal increases with the bit rate, and also as the duty cycle decreases. These factors must be balanced for all of the components in the fiber-optic system.

Any of the representative forms of digital signals that we have shown in Figure 3-10 can be accommodated in the fiber-optic transmission system. The bipolar forms obviously will require a cw type operation (quiescent driving points), but they have the advantage of permitting ac coupling in the electronic circuitry. The unipolar forms contain a dc component which must be accommodated. A final consideration relative to duty cycle must be made in reference to the discussion of optical-carrier multiplexing in Section 3-3.

Throughout this section, we have discussed the digital signal forms of transmission in the framework of a serial data stream. It should be noted that the fiber-optic transmission

scheme offers a new vista for parallel data. The system designer or evaluator should keep this option in mind, with respect to the SDM system discussed in Section 3-3. It is conceivable that in some applications, where the mission bit-stream of a communication system is formulated in serial fashion from a number of (lower bit-rate) parallel data streams, a reconfiguration using a multifiber cable and parallel data in SMD could be beneficial. Lower data rates per fiber can extend the transmission length or reduce the number of repeaters required. These are examples of the possible benefits.

CHAPTER 4

COMMUNICATION SYSTEMS

4-1. INTRODUCTION

There are many types of communication systems in use today, designed for a variety of transmission modes. These range from wire and cable systems to those designed specifically (with special coding and transmission schemes) for very long-range radio circuits. Many of the systems are designed with optimum performance predicated on a well behaved transmission medium. In other words, these systems are essentially designed for operation in a noise limited environment. The special coding and design features are factored in to overcome the noise or interference.

The microwave engineer knows from experience that noise limitation is not always fact. The propagation medium for radio systems is not well behaved at all times, and it can frequently cause severe degradation or complete outages for long periods of time. At the other extreme, wire or cable systems are subject to unexpected EMI with similar results.

The optical-fiber transmission medium offers some new advantages to the designer in both of these problem areas. The utility of this technology is being experienced in former wire-line systems, as a number of commercial installations have been made where the metallic conductors are replaced with a fiber-optic system. Examples can be found in commercial telephone networks, and in military applications for avionics systems. As stated in Chapter 1, our objective is to suggest the methods and to present the design procedures to extend this technology (where possible) into the radio communication networks, where a wide-band microwave link for example, could be replaced with a fiber-optic system. Transmission configurations of this type are technically feasible, and will become more economically viable as the fiber-optic technology continues to expand and improve. The fundamental advantages gained were cited in Chapter 1.

In this chapter we will examine a few typical communication systems in use today (particularly those used by the military in fixed point-to-point networks), and consider the possibility for conversion to fiber-optic transmission. The discussion is not intended to present strict design procedures, but is presented only to provide design options or suggestions for consideration. Once the designer has reached a decision that the proposed methods (or others that he may consider) has merit for his problem, the design procedures presented in other chapters should be helpful in reaching a solution.

This conceptual design area is very important in optical fiber communications. The technology itself is not a communication system, but only a transmission system. Therefore, in order to exploit the advantages it offers, the designer of a communication system must couple into the fiber-optic systems. We will only be able to introduce the concept in this section, and we will limit our considerations to the most common multichannel broadband systems in use today.

4-2. FM/FDM COMMUNICATION SYSTEMS

The FM/FDM system is perhaps the most predominate communication technique today, despite the rapid advent of digital techniques. A great number of these systems are in use around the world, in both commercial and military installations. Some adaptation concepts have already been mentioned in both Chapter 2 and 3 relative to this system. We will expand upon these somewhat here, and suggest other possibilities.

The baseband signal of an FM/FDM system is compartmentalized in a fairly standard fashion (CCITT, recommendations) regardless of the total number of individual channels. Figure 4-1 is an illustration of the compound baseband structure, and shows the hierarchy of the fairly standard FDM practice. The elements of the system are as follows:

1. Channel: a narrow bandwidth interface to the communication source, such as a voice or data

signal. Channels are generally designed for a nominal 3-kHz voice-band signal, and provide a guardband to a total width of 4 kHz. Each channel is furnished with a separate center-frequency carrier in the range of 60 to 108 kHz.

2. Group (G): a group is composed of 12 channels. One sideband of each of the modulated (AM) channels above is combined, and is used to modulate a designated group carrier frequency in the range from 420 to 612 kHz. A group has a BW of 48 kHz.

3. Supergroup (SG): a supergroup is made up of the combination (as the group above) of 5 groups. Supergroup carrier frequencies range from 612 kHz to 2852 kHz. Each supergroup is 240 kHz wide (312 to 552 kHz). A guardband of 4 kHz is provided on each side of a supergroup so that the supergroup carrier frequencies are spaced 248 kHz apart.

As many as 10 supergroups are combined to form a system baseband signal, composed in this case of 600 channels. Many systems however, will be comprised of only one or two supergroups providing 60 to 120 channels of service.

It can be seen from Figure 4-1 that the SG-1 is translated to the baseband using the lower sideband of the modulation, and SG-2 is translated directly without benefit of a carrier. The baseband signal thus has a lower limit of 60 kHz. It extends as high as 2540 kHz for a full 600 channel system.

This brief review of the standard FDM baseband structure is provided in order to facilitate a discussion of how this communication system might be adapted for transmission over a fiber-optic waveguide. There appear to be several options available. The first feature of the fiber-optic transmission method that we should keep in mind is that of the SNR-BW product that usually prevails in the design of the analog methods (see for example Fig. 3-7). The Defense Communication Agency (DCA) establishes required performance parameters for military systems using FDM

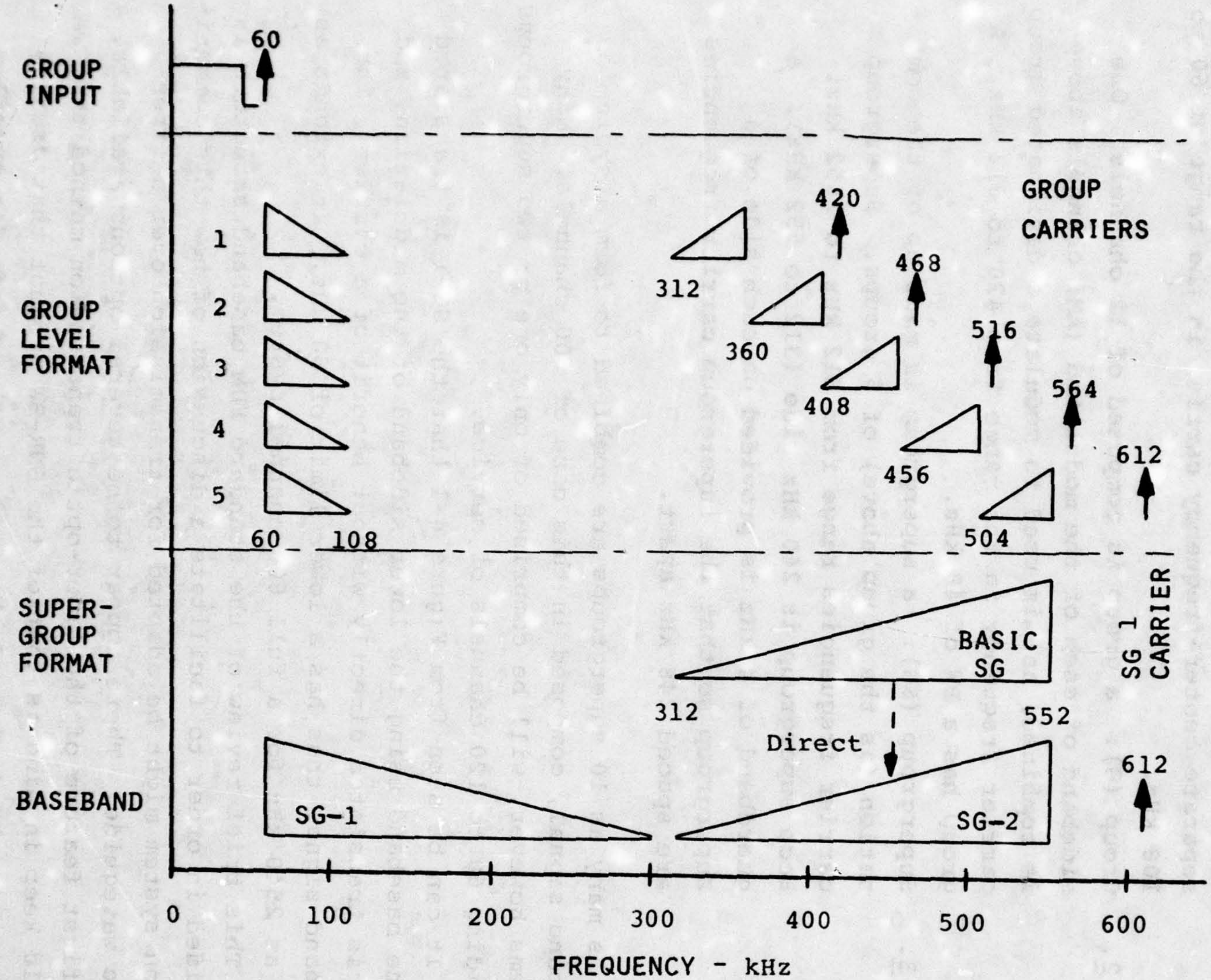


Figure 4-1. Illustration of the baseband signal structure of a typical FDM system.

techniques. These are generally specified as required SNR's in the voice channels, or as a measure of noise in an idle (unused) channel for minimum grades of service. It was pointed out in Chapter 3 how these specified requirements could be transferred to the fiber-optic system, and the required optical receiver SNR calculated to meet the communication system performance. The required optical power at the detector can be achieved through tradeoffs between the baseband signal BW and SNR.

The FDM baseband signal offers the designer several options of signal BW in relation to the above tradeoff. It is not practical to consider the channel level signal among these options, but starting from the group level and above the options are practical. For example, the group (12 channels) occupies a BW of 48 kHz (60 to 180 kHz for each). The FDM system usually provides a signal interface (group level input and output) as a part of the system electronics. Thus, the group level signal would be available for application to the fiber-optics link. Any of the transmission modes discussed in Chapter 3 for analog signals could be applied at this stage for conversion, including the pulse forms. The latter would require the design of sampling and pulse forming circuits that add complexity to the conversion, but if a BW expansion technique such as PPM can be applied for better efficiency and performance in the fiber it should be considered.

The most straightforward conversion can be made directly with the group signal. It could be applied to the optical driver in the continuous signal mode, requiring the smallest BW of transmission. If the SNR-BW tradeoff permits a larger BW however, the group signal could be coupled using the subcarrier FM with the accompanying performance improvement. These methods are illustrated in block diagram form of Figure 4-2. Each group of the baseband would be coupled to an independent optical source and fiber in the optical cable. The structure would require 5 fibers to handle each supergroup used in the system baseband. It would be a practical configuration for those systems using

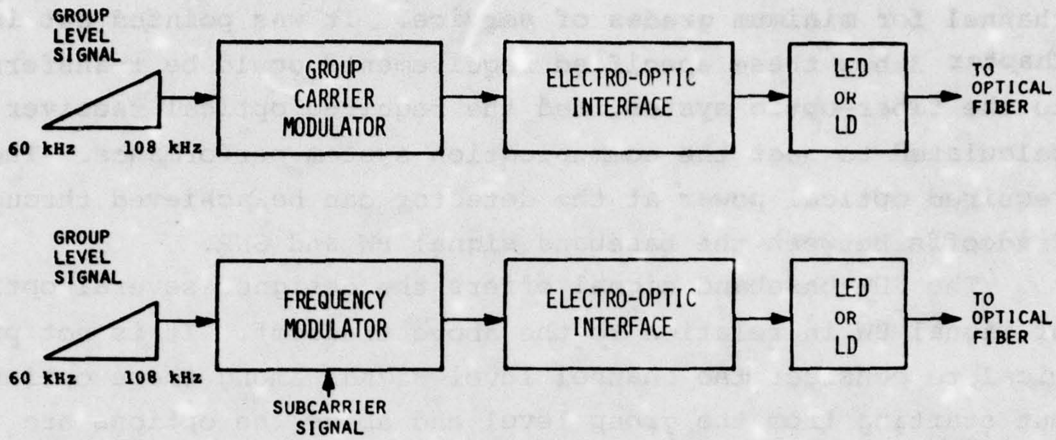


Figure 4-2. Methods of coupling FDM baseband signals into an optical fiber system.

two supergroups, or a total of 120 channels. Beyond this, the number of fibers in the cable would be impractical.

The second level for conversion in the FDM baseband is at the supergroup level. The process would be the same as that outlined above for the group level, with the exception, of course, that the BW is on the order of 240 kHz for each supergroup. Thus, the SNR-BW tradeoff will result in shorter transmission distances for the same SNR and the same fiber source combination as considered for the group level conversion. However, only one transmission fiber would be necessary for each supergroup (5 groups), and thus, in design comparisons based on cost factors, a better fiber could perhaps be specified to extend the performance distance at no (or only slight) increase in costs.

In applying either of the above conversions, there are two additional design requirements that must be met. These are (1) to provide for the traditional order-wire and fault-alarm signals necessary for the particular FDM system, and (2) to maintain the signal integrity required between the FDM multiplex and demultiplex equipment. Variation in system design precludes presenting any specific details for the first requirement. Order-wire communication is provided in different ways in different systems.

The possibilities include adding the order-wire and alarm signals by a hybrid mix to any of the group or supergroup signals; carrying them by twisted-wire pairs in a combination fiber/wire cable; or modulating the order-wire information on the pilot signal discussed below.

The requirement for signal integrity between the transmitter multiplex and the receiver demultiplex is accomplished in most systems with the use of a pilot tone. For example, a common technique is to provide a 60 kHz pilot tone as a reference for the group carrier frequencies. The pilot tone is added to the baseband signal through the supergroup hybrid unit in most systems, so that it occupies a position equivalent to the lowest frequency carried in Group No. 1. Therefore, in the conversion techniques outlined above, the 60 kHz pilot tone may be combined with G-1, and carried in the fiber that transmits G-1 or SG-1 as the case may be.

Obviously, a system configuration based on a mixture of the above two conversion levels could be used. For example, if a particular group level is dropped from a network after the first link and other groups are transmitted through, the cable design can be made to accommodate these configurations. The economies might dictate a single less expensive fiber for the group to be dropped out in the initial link, or conversely, to use a supergroup conversion over the first link, and use group conversion for the remaining through groups. These are only illustrations of configuration alternatives that may arise in design.

Another configuration alternative that may be encountered in certain FDM systems should be noted. There are data and voice channel modems in operation today that are designed to interface with an FDM system either at group level or supergroup level, but are digital TDM systems. When these are encountered, the option of coupling the modems directly to an optical fiber in the digital transmission mode should generally be used. A specific example of a system of this type is discussed in the following section.

4-3. TDM COMMUNICATION STSTEMS

The TDM communication system is ideally suited for application to the fiber optic transmission methods. This fact has been discussed in both Chapters 2 and 3, and the design procedures in Chapter 6 are oriented toward the digital system.

The options for mating an existing TDM facility to a fiber-optic transmission cable are very similar to those given for the FDM technique. For example, the TDM baseband signal is composed of low-level bit streams representing either a basic channel or several channels strapped together to form a bit-rate capability higher than an individual channel. These bit streams are then combined into a single serial bit stream to form the mission or baseband signal. Specific time slots are assigned to each channel (or strapped channels) in the mission bit-stream signal.

We have already mentioned in Chapter 3 the possibilities of breaking down the mission bit stream into its lower bit-rate components, just as the FDM baseband signal was broken down into its narrower bandwidth components. Conceptual design methods are also very similar. The BER performance criteria for each subset of the mission bit stream can be determined and specified separately. Thus, each stream can be coupled to an individual optical source and transmission fiber. A number of fibers in a cable can then accommodate the entire baseband in subsets, forming a parallel SDM transmission format. A recently introduced multilaser driving source was shown in Chapter 3 that is ideally suited for these applications; for both the FDM and TDM configurations suggested above.

The objective of dividing the baseband signal in both multiplex techniques is to extend the possible transmission length by lowering the signal bit rate or bandwidth required of each fiber used. If the performance criteria can be met for the complete mission signal within a single fiber over the required distance, these techniques are not necessary. However, the multifiber transmission method (SDM) offers the designer an option of parallel digital transmission for other applications.

4-4. SPECIAL MODEM REQUIREMENTS

There are a few TDM modems in military use that deserve a special note. They have operational features that differ somewhat from the more traditional TDM systems, and will require particular considerations in adapting them to the fiber-optic transmission mode. The first system we consider is the Vicom* digital multiplex system. This system is designed to format a 1.544 Mb/s bit stream from 8 T1-carrier terminals. One unique feature of this system is the output signal form used for transmission in a radio circuit. The mission bit stream is developed initially in an NRZ unipolar form. However, the radio transmission mode for standard operation is FM. In order to lower the overall bandwidth required for the transmission signal, the NRZ signal is filtered and re-formed into a three-level partial response signal. The details of this process can be followed using the sketch of Figure 4-3.

A bit pulse is so shaped by the filter network that its peak output is delayed and is spread in time into the following bit-time. The composite output signal from the filter is shown in (d) of Figure 4-3. It can be seen that two slicing levels are necessary to detect this signal, and recover the binary signal. The two extreme values of the analog signal are obviously interpreted as multiple "1's" (high level) or multiple "0's" (low level). At other sampling times, a signal value above the median level is interpreted as a transition from a "0" to a "1", and a level below the median indicates the opposite transition. The coding interpretation of this signal is not too important for our purpose, but the reader should be aware of the format.

An important feature of the Vicom system hardware should be pointed out. The electronics are included to formulate the analog-type signal illustrated in Figure 4-3(d). This signal could be applied to the fiber-optic waveguide using the continuous analog transmission methods in Chapter 3. The BW of the three-level partial response signal is roughly 1/4 of the basic bit rate.

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*Vicom is a registered trademark, used by Vicom, a division of Vidar Corporation, Mountain View, California.

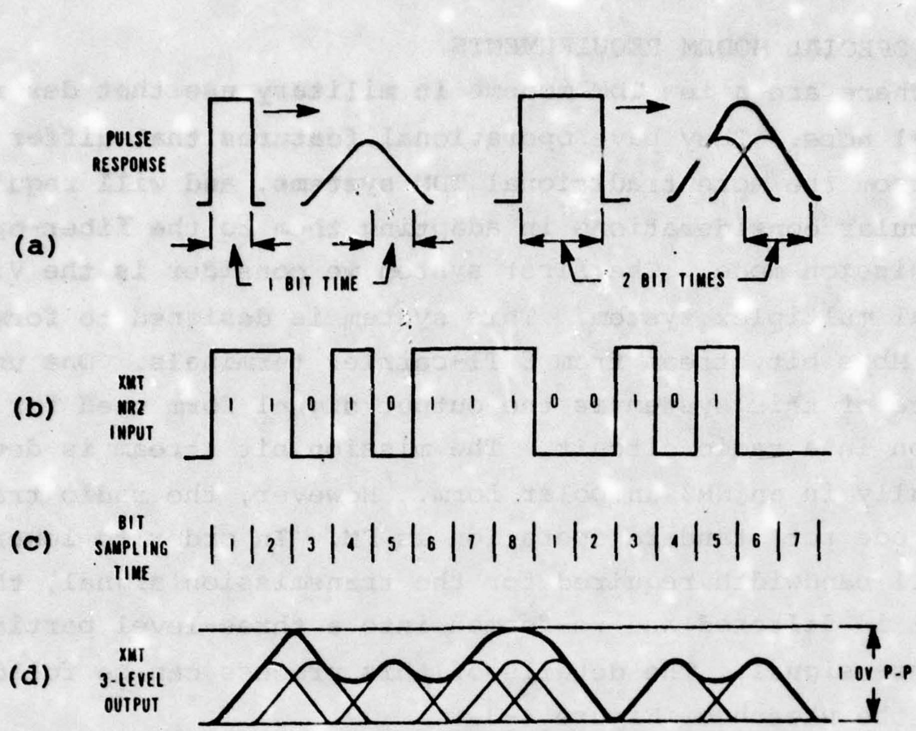


Figure 4-3. Conversion of an NRZ signal to a three-level partial response signal.

Alternatively, the Vicom units provide signal strapping for application to digital radio systems. In this mode, the filter interface is bypassed and the output signal from the modem is the NRZ form of Figure 4-3(b). Therefore, the Vicom system offers the designer a choice between analog or a pulse transmission, with the associated greater BW requirement for the latter.

Another class of digital modems, including interconnect facilities (ICF), either in use or planned for military application, has special requirements for timing signals. Some of the modems in this class are specified to be programmable; i.e., a number of possible channels are specified, but their configuration is variable. For example, a given number of base channels can be programed (or strapped) to form a channel for higher bit rates, and the allocation of time slots is also programmable. This flexibility adds complexity to the optical-fiber interface if any division of the mission bit stream is required. However, the specification for timing signals is the most important

consideration. Some modems in this class specify that a channel and timing signal be developed and multiplexed into the baseband signal along with the information signal. The timing signal is specified to be a 50% duty-cycle rectangular signal at the base clock-rate of the data signal. The phase and time relationships between the timing signal and the data signal that must be maintained are also specified. These requirements are illustrated in Figure 4-4. Typical requirements for the parameters in Figure 4-4(a) are as follows:

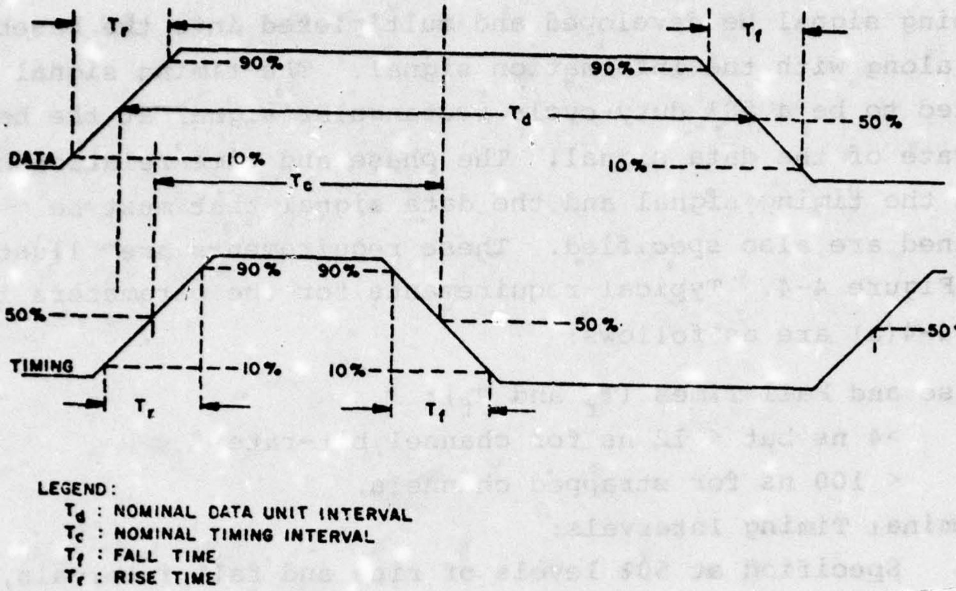
Rise and Fall Times (T_r and T_f):

> >4 ns but < 12 ns for channel bit-rate
>
> < 100 ns for strapped channels.

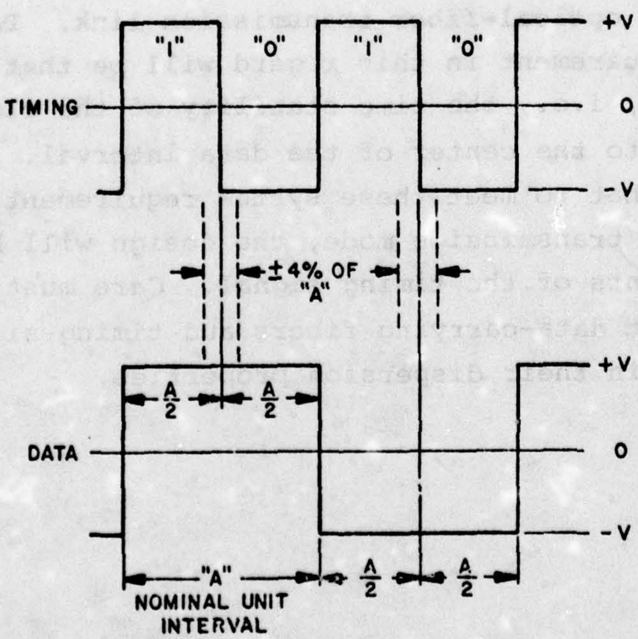
Nominal Timing Intervals:

> Specified at 50% levels of rise and fall intervals, with a stability of ± 1 part in 10^5 per month at a stabilized ambient temperature of 20°C.

The integrity of these parameters must be maintained in the design of the optical-fiber transmission link. Perhaps the most stringent requirement in this regard will be that indicated in Figure 4-4(b), i.e., the time stability of the clock transition with respect to the center of the data interval. It must be pointed out that to meet these system requirements in the optical-fiber transmission mode, the design will be dictated by the requirements of the timing signal. Care must also be taken to insure that data-carrying fibers and timing-signal fibers are well matched in their dispersion properties.



(a) Parameter definitions and phase relationships



(b) Data/time stability requirements

Figure 4-4. Specified parameters and relationships for data and timing signals for special TDM modems.

CHAPTER 5

ELECTRO-OPTICAL INTERFACE

5-1. INTRODUCTION

Interfacing the optical-fiber transmission system to electronic communications equipment is very important in the total systems concept. As pointed out in Chapter 4, the optical-fiber and its associated components form only a transmission mechanism for communication signals that are generated in electronic equipment. These signals must be converted from the electrical domain into the optical regime at the transmitter terminal, and reconverted at the receiver terminal.

Chapter 4 outlined the methods that can be used to match signal parameters such as bandwidth or digital bit rates to the optical-fiber transmission-length characteristics. It is the purpose of this chapter to outline the fundamental requirements of accomplishing this interface, and to present typical examples of circuitry used for the electro-optical conversion. The detailed technical aspects of the interface design could easily be a complete and independent study beyond the magnitude of this handbook. We will, therefore, not attempt to present a comprehensive treatment here, but limit our discussion to the important features and design goals. Examples of applicable circuitry that have been found useful will be presented as guidelines.

Repeater systems are included in this discussion, since they require the same electro-optical interface design as do the terminal systems. There is no optical repeater per se that is the counterpart of a translation amplifier used, for example, in FDM systems. The information signal must be detected at an optical repeater, and used to modulate another light source that drives the continuing fiber. This requirement is not a disadvantage in the optical-fiber transmission of pulsed signals, however, since it is desirable to regenerate the signals in any tandem-link system (Section 3-5 b.).

5-2. OPTICAL SOURCE ELECTRONICS

The function of the driving circuit for an optical source is to accept an electrical input signal and to convert it to a current drive appropriate for the selected device. The sources we are considering are limited to the LED and LD devices discussed in Chapter 2. The requirements of the driving circuit may vary with the particular source selected, and with the information signal (analog or digital). There are, however, some common requirements which can be delineated as:

1. The circuit should supply no more than the recommended peak or average drive current for the particular source.
2. Bandwidth and/or switching speed of the circuitry must match that of the information signal.
3. It must match the dynamic range of the driving or modulating signal.
4. The circuit should include a method for establishing and/or varying the quiescent bias current required for the particular driving signal.
5. The design may require special compensation features to overcome problems in impedance matching, non-linear characteristics of the driver, and environmental problems such as temperature.

a. LED Drivers

The driver for an LED source requires less drive current, because of the generally lower bias and power output of the device as compared with the LD sources. For low-frequency analog circuits, an operational amplifier in conjunction with a current regulator is generally all that is required for an LED. Two examples of circuits capable of driving an LED over a signal BW of approximately 1 MHz are shown in Figure 5-1. The circuit of (a) is a simple shunt drive configuration (Hoss and Weigl, 1975) which provides an approximate 100 mA rectangular constant-current drive to the LED.

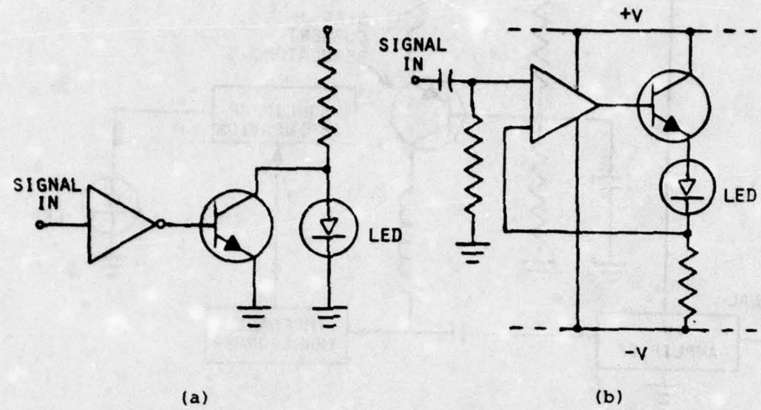


Figure 5-1. Two examples of low frequency analog driving circuits for an LED.

The circuit in (b) of Figure 5-1 includes the nonlinear impedance of the LED in the feedback loop of the op-amp. The signal drive current is established with the input signal (ac coupled) appearing across the resistance R (Casper, 1975). The zero-signal bias level is established by the relationship chosen for the reference point of the input signal, the value of the negative voltage supply, and the value of R. The BW limitation of this type circuit is a combination of the gain-BW product of the op-amp and the nonlinear characteristic of the particular LED.

A typical example of an analog driving curcuit for wideband signals, or for subcarrier modulation of the LED source, is shown in Figure 5-2. The quiescent bias current in this configuration is established by choice of the regulator used and the power supply voltage. An impedance transformer is shown in block form, used to match the output requirement for the driving amplifier and coupling into the LED drive current path. The diagram also illustrates the location of a compensation network for the non-linearity features of the particular LED. Circuits of this type are useful over signal BW on the order of 100 MHz and beyond.

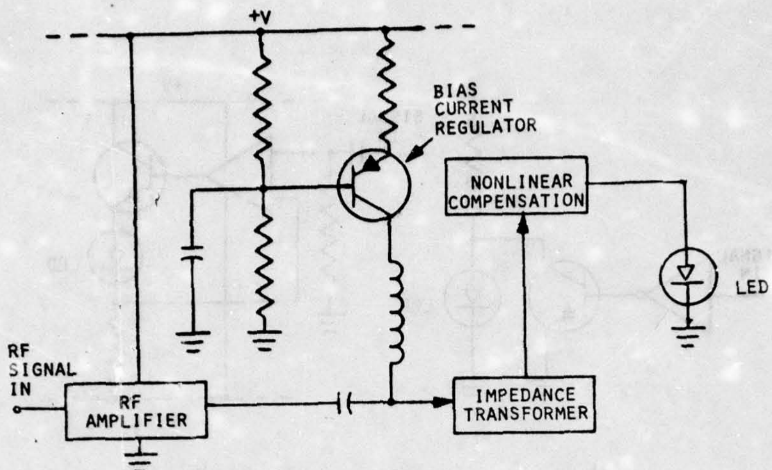


Figure 5-2. Example of a wideband analog driving circuit.

Application of a circuit of this type has been reported by Pan (1975). A standard 50SL rf amplifier was used for the base-band signal input. The impedance transformer was a tapered line, matching the amplifier to an LED that had an impedance (occassionally inductive) on the order of 3 to 7 ohms. The nonlinear matching network used was an RLC π-network designed to compensate the characteristic of the system for a 1 km length of the chosen fiber. Good linearity properties are reported and a flat frequency response from a few MHz to 500 MHz was cited by this author. These results are given only as an indication of the performance that might be expected from this typical circuit.

As noted in previous sections, the nonlinear properties of the LED itself is the largest problem for analog systems. This characteristic is depicted in Figure 5-3, where the quiescent bias current is shown as i_B, and the plus and minus swing of the modulating signal is labeled as i_Δ. The modulation index m for intensity modulation is shown as the ratio of these quantities. Note that equal swings in the two directions produce an unequal change in the optical power output. To compensate for the resulting distortion, the drive circuit could be designed to produce a higher positive swing above i_B in order to match the optical power output change with reference to the bias. The theoretical compensation is sketched in Figure 5-3.

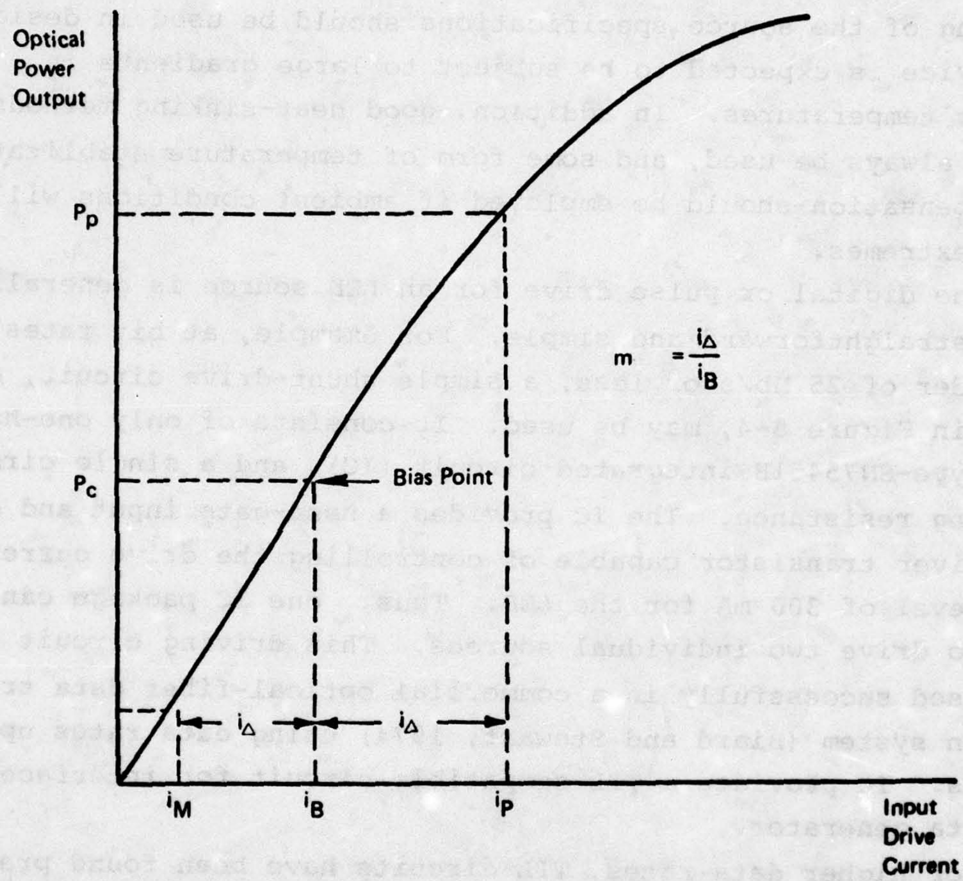


Figure 5-3. Representation of output of LED (or LD) above threshold as a function of drive current.

One very important consideration in the application of LED's is the ambient temperature, and care must be taken to provide adequate heat dissipation. The optical power output of these devices can change drastically with junction temperature. Shifts in the peak of the radiant spectrum may also occur, particularly if the device is driven close to its characteristic limits. Derating of the source specifications should be used in design if the device is expected to be subject to large gradients in ambient temperatures. In addition, good heat-sinking methods should always be used, and some form of temperature stablization or compensation should be employed if ambient conditions will reach extremes.

The digital or pulse drive for an LED source is generally quite straightforward and simple. For example, at bit rates on the order of 25 Mb/s or less, a simple shunt-drive circuit, as shown in Figure 5-4, may be used. It consists of only one-half of a type-SN75451B-integrated circuit (IC), and a single circuit limiting resistance. The IC provides a nand-gate input and an npn driver transistor capable of controlling the drive current up to a level of 300 mA for the LED. Thus, one IC package can be used to drive two individual sources. This driving circuit has been used successfully in a commercial optical-fiber data transmission system (Biard and Stewart, 1974) using data rates up to 15 Mb/s. It provides a TTL compatible circuit for interface with the data generator.

For higher data rates, TTL circuits have been found practical for rates up to and beyond 100 Mb/s. A typical circuit using this logic is shown in Figure 5-5. Here, two pnp transistors are connected in a current-shunting arrangement with Schottky TTL differential drive, and a npn transistor is used as a constant current sink. In one state, the current noted as 2I in the diagram is shunted to ground and the I-current is pulled through the LED source. In the opposite state, the constant current of the npn transistor is supplied by the 2I path and switches the I-current into the LED in the reverse direction to turn it

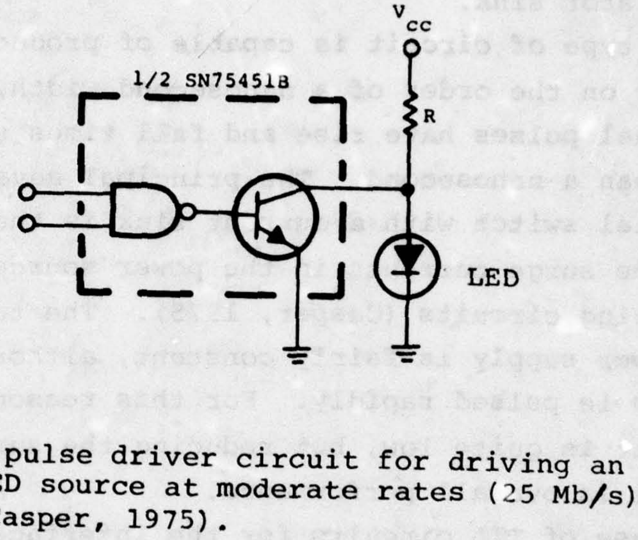


Figure 5-4. A pulse driver circuit for driving an LED source at moderate rates (25 Mb/s) (Casper, 1975).

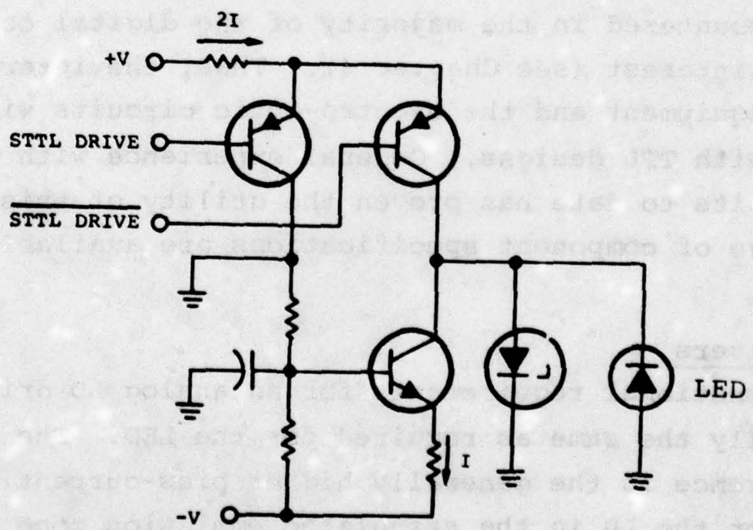


Figure 5-5. A high data-rate driver for an LED source, using Schottky TTL constant current switch (Casper, 1975).

off rapidly. The Schottky diode in shunt with the LED clamps the reverse potential in this state. A variation of this circuit using ECL can also be used, providing an npn switch-pair and a pnp transistor sink.

This type of circuit is capable of producing current pulses in the LED on the order of a nanosecond width, even though the input signal pulses have rise and fall times substantially greater than a nanosecond. The principal advantage of the differential switch with a current sink is that it significantly reduces the surge currents in the power source, as compared with other pulsing circuits (Casper, 1975). The total current drain on the power supply is fairly constant, although the current flow in the LED is pulsed rapidly. For this reason, the efficiency of the circuit is quite low, but reducing the surge currents can be of benefit in overall performance.

The use of TTL circuits for the interface at both the optical source and detector has some definite advantages. For example, it is quite probable that this logic and its associated levels will be encountered in the majority of the digital communication systems of interest (see Chapter 4). Thus, the interface problems with this equipment and the electro-optic circuits will be minimized with TTL designs. General experience with the electro-optic circuits to date has proven the utility of this logic, and a wide range of component specifications are available to the designer.

b. LD Drivers

The functional requirements for an analog LD driving circuit are basically the same as required for the LED. The one significant difference is the generally higher bias-current drive required for the LD in the stimulated emmission zone (lasing region). Therefore, the analog circuits presented in the previous section are also applicable to the LD, with proper adjustments of the current supply and the capability of the bias current regulator transistor.

There are, however, choices between LED and LD sources that operate with nearly the same bias currents. In these cases, the drive circuits are essentially equivalent, with the exception that stabilization for temperature effects may be required for the LD source. The advantage of the LD in terms of optical power launched into a fiber can be seen from Figure 5-6. Here the power launched into a fiber as a function of NA is shown for an LED and an LD, each operating at 150 mA bias current (Eppes et al., 1976). Note the higher optical power available from the LD, and also its higher coupling efficiency due to the more coherent emission.

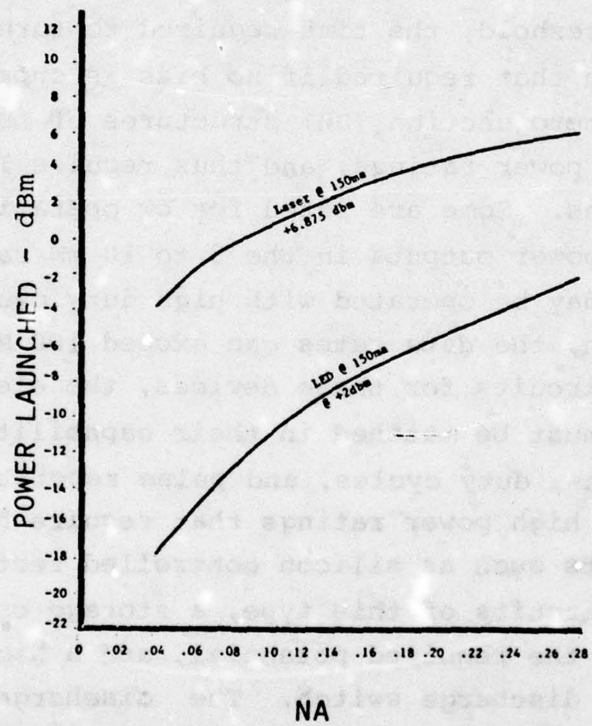


Figure 5-6. Comparison of launched optical power for an LED and an LD with equal bias current (Goell et al., 1975).

For driving an LD in the digital or pulse modes, there is a tradeoff that usually must be considered between peak current (consequently, peak optical power output) and the signaling rate. Some LD's are capable of peak power output as high as 10 W. However, due to the requirement for dissipating junction heat at

the high current associated with such a power level, the duty cycle and pulse width must be adjusted so that adequate cooling time is provided. For example, a particular single-heterojunction LD in this power class is specified for a maximum pulse width of 20 ns and a duty cycle of 0.1%. Driving this unit at peak power will thus limit the data rate to approximately 50 KHz. Using a pulse width of 10 ns with the same duty cycle restriction will permit a doubling of the data rate to 100 KHz. This type of driving tradeoff can continue with the constraints imposed by the rise- and fall-time limits of the particular device, and with respect to the bias point. As noted previously if the LD is biased near the threshold, the time required to turn on the device is less than that required if no bias is supplied.

The double-heterojunction (DH) structures of LD's are generally of lower power ratings, and thus require lower drive current and voltages. Some are rated for cw operation at room temperatures with power outputs in the 5 to 10 mW range. As a consequence, they may be operated with high duty cycles; and as we have seen, the data rates can exceed 100 Mb/s. In designing driver circuits for these devices, the electronic components chosen must be matched in their capabilities to the desired pulse widths, duty cycles, and pulse repetition rates.

For LD's with high power ratings that require high drive currents, components such as silicon controlled rectifiers (SCR) can be used. In circuits of this type, a storage capacitor is usually charged to the required potential, and a high-current SCR is used as a rapid discharge switch. The discharge current is forced through the LD. Transistors can be used to regulate the storage charge. By nature, the SCR switch is relatively slow, and obviously the pulse rate of such a drive will be restricted. Drive currents can be in the order of 20 A and higher.

For lower power LD's, the driving circuit described above may be configured using transistors in the place of SCR's. A typical circuit is shown in Figure 5-7, capable of up to 20 A with the components indicated and a data rate of approximately

100 kHz. Lower current transistors with faster logic speeds may be selected for use in this circuit to drive the high-data-rate LD sources.

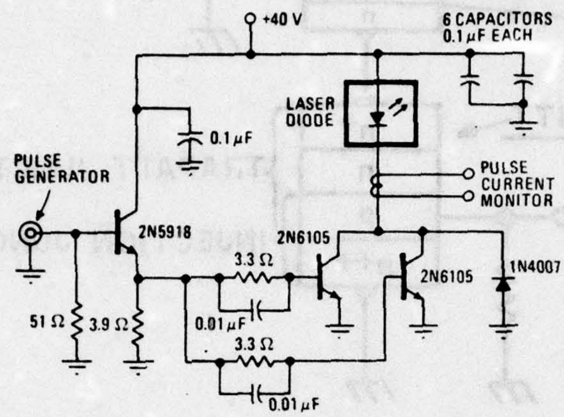


Figure 5-7. A typical driving circuit for a high-power LD, with peak current on the order of 20 A (O'Brien, 1976).

A nanosecond pulsing circuit for use with a DH-type LD has been reported by Kawamoto and Miller (1975). The circuit employs a three terminal Trapatt device, which consists of a punch-through diode with an added impurity profile having an n^{++} layer to form a second junction (a control junction). The Trapatt junction is reverse biased near the avalanche level, and the control junction is used to inject carriers to trigger the trapped plasma. The device is illustrated in Figure 5-8 and has been given the acronym CARITT: CARrier Injection Triggered Trapatt. In demonstrating this circuit, an epitaxial bipolar transistor was selected to drive the CARITT device. Using a stripe-geometry LD and an input of 0.6 V, the CARITT device produced one nano-second current pulses of 6 A. The optical pulse from the LD was measured to have a width of 1 ns, even when the input pulse widths were varied over a range of 2.5 ns to 100 ns.

The authors (Kawamoto and Miller, 1975) who tested this circuit report that the LD operated without burn-out even at a drive current level as high as ten times the dc lasing threshold.

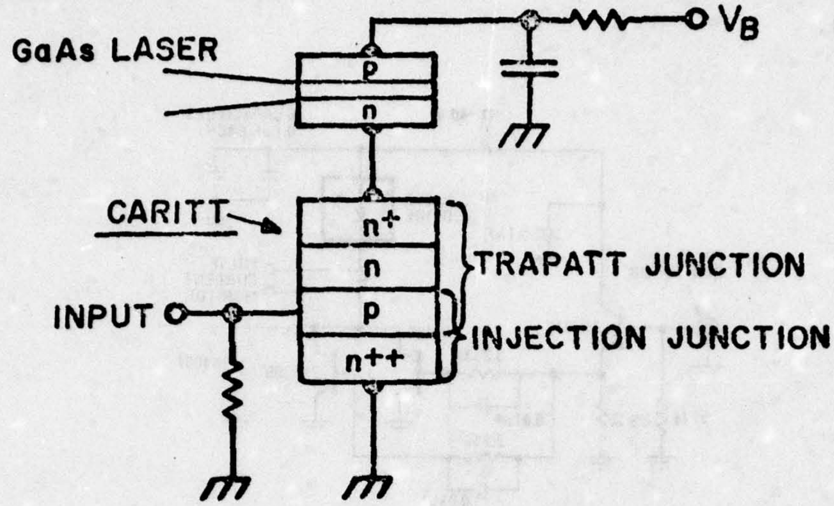


Figure 5-8. Carrier injection triggered TRAPATT (CARITT) device driving a GaAlAs laser diode (Kawamoto & Miller, 1975).

Thus, a very narrow optical pulse is generated with a power output as high as 2 W, and very fast turn-on from threshold. The technique appears to have significant advantages for driving both the LD and the associated fiber waveguide. Further background for the Trapatt device may be found from Kawamoto (1973).

5-3. OPTICAL DETECTOR ELECTRONICS

In this section, we will outline the current state of the art in electronic circuits used with the optical detectors presented in Chapter 2. Typical circuits and characteristics for both the PIN diodes and APD devices will be considered.

As discussed in Chapter 2, the photodetector diode is a device that is operated with either a zero bias voltage (photovoltaic mode), or with a reverse bias voltage (photoconductive mode). In the former case, the diode is considered as a voltage source, and in the photoconductor mode it becomes a current source for circuit design considerations.

The primary objective in the design of the detector electronics is to maximize the sensitivity (minimize the noise),

which is a function of both the chosen optical detector and the associated preamplifier. To accomplish this objective, the input capacitance and the noise BW of the preamplifier should be minimized. The total input capacitance is composed of the detector capacitance, the input capacitance of the preamplifier, and any stray circuit capacitance. The noise BW is usually much larger than the signal BW of interest, and it is therefore important to design for an overall BW no larger than absolutely necessary for the signal, and performance requirements. For a digital or pulse detector circuit, the speed of response is the critical parameter. The preamplifier circuit should ideally raise the detector signal level to a magnitude that is easily handled by conventional analog or digital electronics without adding excess noise or degrading the performance of the detector. High signal output and high sensitivity imply a high preamplifier input impedance; however, large BW or high-speed response implies low impedance. In addition, resistive loads and bias resistors should be avoided in order to minimize the thermal noise and resulting degradation of the SNR.

a. PIN Detector Circuits

A circuit that meets most of the above demands for a PIN diode is one known as a transimpedance amplifier. This circuit combines the desirable features of low input impedance, low input noise, high gain, and dc coupling to the photodiode. A simple yet effective circuit schematic is shown in Figure 5-9. This preamplifier may be dc coupled to a post amplifier to provide the signal gain required. The latter may be an operational amplifier for analog application, or a high speed comparator which provides a TTL compatible signal to digital electronic systems. This type of circuit has found practical application in a fiber optic system operating with a PDM signal format near 1 MHz clock rate (Hoss and Weigl, 1975).

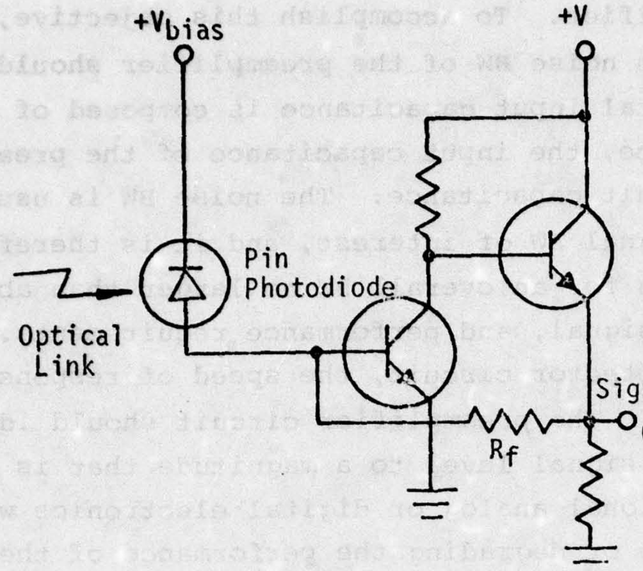


Figure 5-9. Optical detector circuit (Hoss & Weigl, 1975).

A typical detector circuit employing a PIN diode and a variation of the transimpedance preamplifier discussed above is shown in Figure 5-10. Here an FET unit is used in the preamplifier which sets the overall noise performance of the photodector-amplifier combination (Wendland, et al., 1976). Operating this circuit in a 10 MHz fiber-optic link provided an SNR on the order of 7 dB with input optical power levels of approximately 10 nW. The input impedance of the preamplifier is on the order of 10 to 50 Ω, providing a good operating load line for the PIN diode, and resulting in good linear operation and frequency response.

In general, it has been found that FET units provide good characteristics and performance in circuits requiring signal BW up to about 10 MHz. Bipolar transistors have been found most effective at frequencies above 10 MHz, and in association with the APD detectors discussed below.

For many applications in analog systems, it may be desirable to follow the detector diode with an operational amplifier. There are advantages to be gained in such configurations,

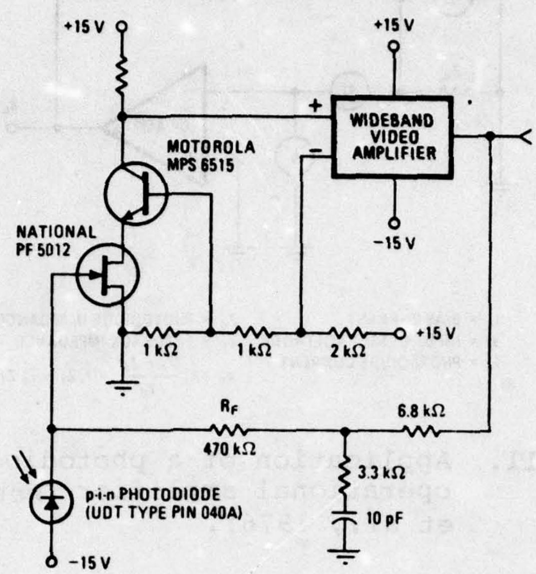


Figure 5-10. A typical detector circuit using a PIN photodetector and a transimpedance preamplifier circuit(Wendland et al., 1976).

particularly for those detectors designed with a guard-ring diode (see Section 2-4 b.). Performance of these circuits is limited to frequencies on the order of 5 MHz and less, primarily due to the characteristics of the op-amps available. The configuration of this type of circuit is illustrated in Figure 5-11, where the parameters are each defined in the figure. Note that the detected signal output is proportional to the product of the photodiode current i_d and the feedback impedance around the op-amp. The noise performance of this type circuit is usually set by the noise voltage of the amplifier - the Johnson noise of the feedback resistor and the input noise voltage - for wideband applications. The input noise voltage from the detector diode should be maintained as low as possible. As noted in Chapter 2, the guard-ring structure helps in this regard by shunting the noise currents away from the feedback or load resistance of the circuit. The typical bias circuit for a guard-ring device is sketched in Figure 5-12.

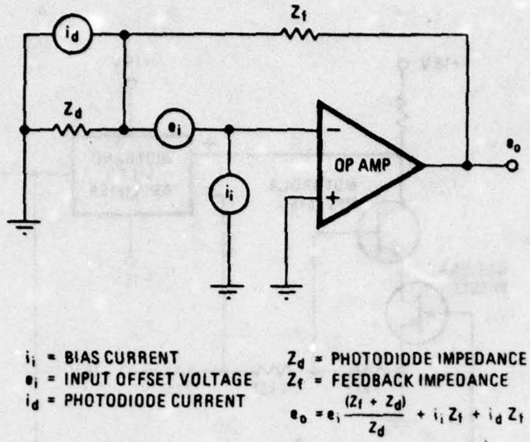


Figure 5-11. Application of a photodiode to an operational amplifier (Wendland et al., 1976).

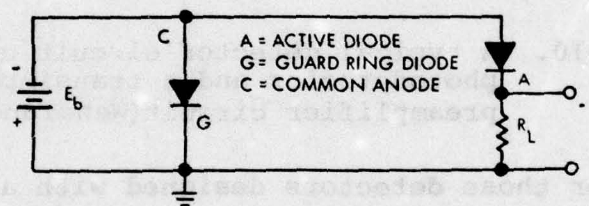


Figure 5-12. A typical bias circuit for a photodetector with a guard-ring diode.

When the guard-ring unit is used in association with an operational amplifier, there are two basic configurations that may be used. These are shown in the diagrams of Figure 5-13. In each case, the photodiode dark current flowing through the feedback resistance around the op-amp produces a dc offset potential at the output of the amplifier. This is compensated for, in the circuit of Figure 5-13(a), by the addition of a compensating current at the summing junction through the resistance R (shown with the dashed lines). However, this technique is likely to raise the input noise due to the added resistor at the amplifier input. An alternative method of compensation would be to provide a dc restorer circuit at the output of the amplifier. Another simple method of compensation is shown with the circuit of Figure 5-13(b). Here an offset null control is

incorporated into the amplifier output circuitry. The adjustment shown for R_C in the circuit permits compensation internally for the dark-current offset (can be nulled out), and the arrangement does not add additional resistive noise at the input to the amplifier (EG&G, 1977).

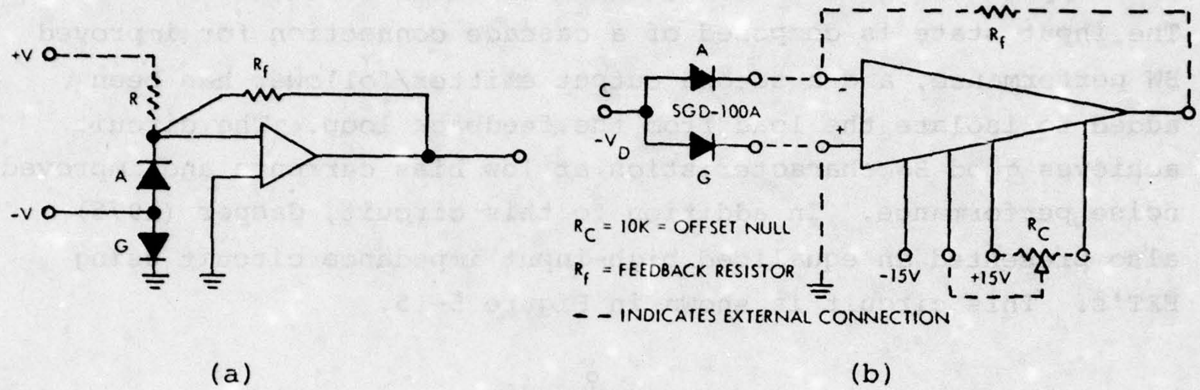


Figure 5-13. Circuits for the application of a guard-ring photodetector with an operational amplifier (EG&G, 1977).

b. APD Detector Circuits

As discussed in Chapter 2, the APD is constructed from the same basic semiconductor material as the PIN diode. Thus, the preamplifier circuits for use with the APD can follow very much the same lines as presented in the previous section for the PIN diode. There are, however, two fundamental differences to consider. First, the APD requires a much higher reverse bias voltage than the PIN diode. Secondly, the APD provides internal gain which also amplifies the noise input. However, it was shown in Section 2-4 d., that an optimum gain may be established which minimizes the effect of the amplified noise on the overall SNR. Also, when the APD is used at signaling rates above about 1 MHz the noise limitations are set by the preamplifier circuit and not by the detector. Thus, the device has application at the higher signal rates.

The basic transimpedance preamplifier shown in Figure 5-9 can be used effectively with the APD. With the high open-loop

gain of this circuit, the closed-loop input impedance is low. The combination minimizes the detector capacitance/input resistance time constant and extends the detector BW without equalization.

Casper (1975) has discussed an improved version of the basic transimpedance circuit above, which is shown in Figure 5-14. The input state is composed of a cascade connection for improved BW performance, and a second output emitter/follower has been added to isolate the load from the feedback loop. The circuit achieves good BW characteristics at low bias currents and improved noise performance. In addition to this circuit, Casper (1975) also presented an equalized high-input impedance circuit using FET's. This circuit is shown in Figure 5-15.

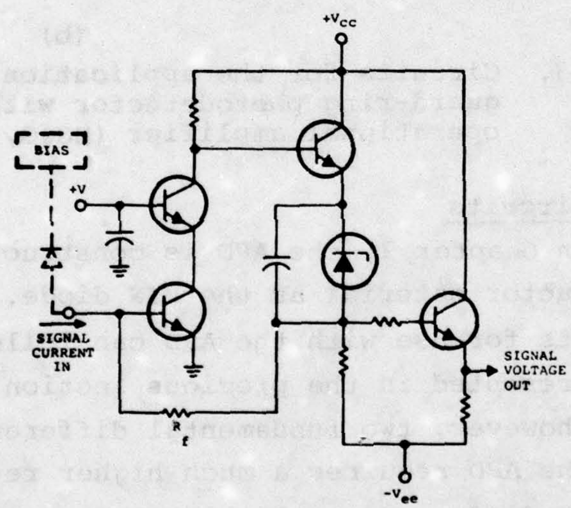


Figure 5-14. An improved version of the trans-impedance (shunt feedback) preamplifier circuit (Casper, 1975).

This circuit was first discussed by Goell (1974). The input load resistor is usually made much larger than normal for the resistance-detector capacitance constraint for the desired BW. The value is bounded only by the permissable detector bias modulation produced by the signal current through the load R_L. The first two FET stages provide voltage gain, and are driven by a follower-buffer stage with an equalizing network at the output.

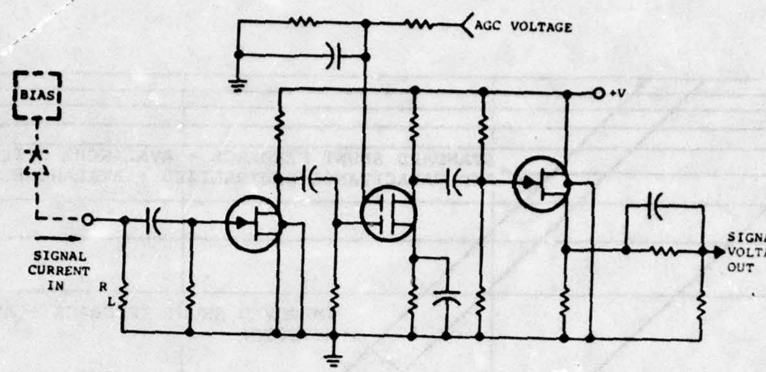


Figure 5-15. An equalized high input impedance preamplifier using FET's (Casper, 1975).

This network is used to compensate for the input frequency rolloff due to the higher-than-normal input RC product. The compensation RC network can be designed to achieve an overall flat response over the BW of interest. The second stage is composed of a dual-gate MOSFET, which provides for an automatic gain control (AGC) fed from the following amplifier(s). Casper (1975) has reported that this circuit is capable of providing up to 8 dB better noise performance than the basic trans-impedance circuit of Figure 5-9. This can also be seen from Figure 5-16, where the theoretical APD detector-preamplifier noise performance of three circuits are compared, based on the noise equivalent power (NEP). The three circuits compared here are those shown in Figures 5-9, 5-14, and 5-15, where they each are assumed coupled to the same high-grade APD. Other parameters and assumptions for these performance curves are as follows:

Temperature: 25° C.
Detector NEP constant with current gain M.
All preamplifiers designed for 10 MHz BW.

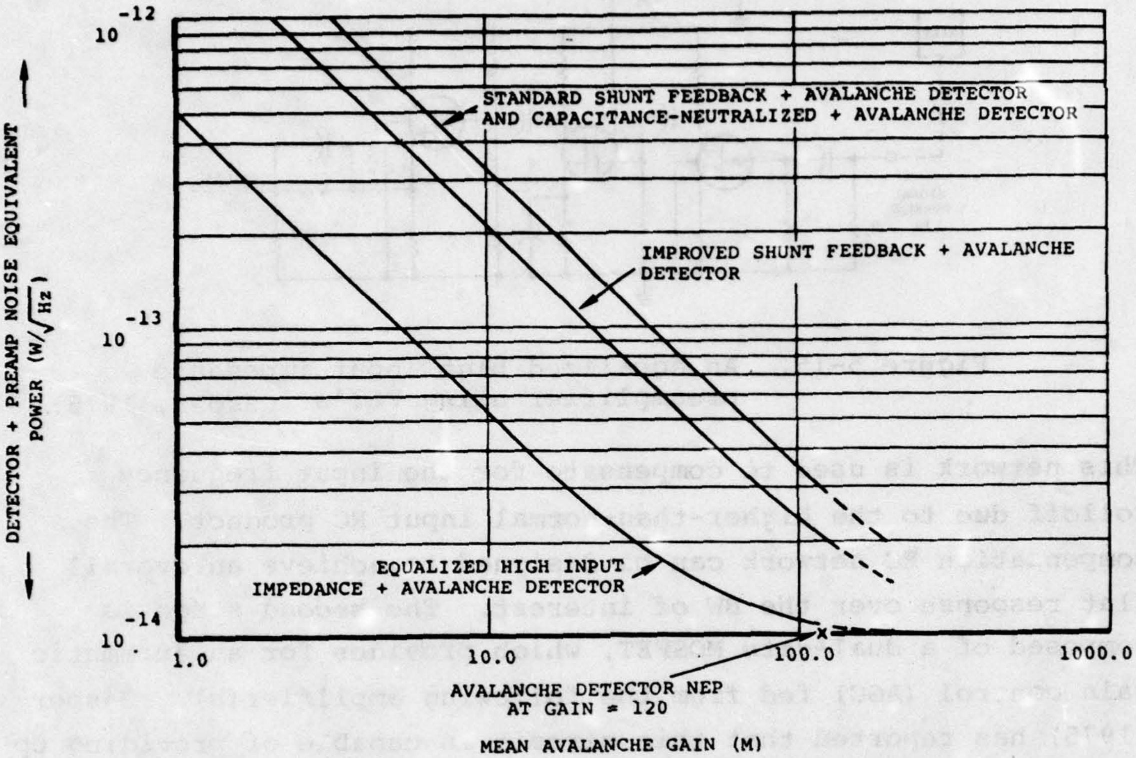


Figure 5-16. Calculated performance of three typical preamplifier circuits with the same APD (Casper, 1975).

It can be seen from these results that the 10 MHz BW represents the approximate upper bound for the detector-limited performance, with state-of-the-art components (APD gains on the order of M=100) and the advanced preamplifier designs.

As noted earlier, the performance of the APD device is degraded by environmental influences, primarily temperature. If the ambient conditions are severe, some form of temperature compensation must be used. One technique (Goell, 1974) uses a feedback gain control such as the AGC system used in the circuit of Figure 5-15. If the temperature drifts are slow, the AGC circuit will compensate for the change in avalanche gain with temperature (see Figure 2-26). For more critical situations, the APD device might best be applied in a temperature-controlled package that protects it from ambient changes, and provides a heavy heat sink

to maintain the junction temperature as constant as possible for the driving conditions.

Temperature control for the APD is essentially limited to applications in the analog signal domain, where the magnitude level stability is important. In the digital or pulse forms (other than PAM) of transmission, the magnitude is not the critical detection parameter. Thus, the APD may be found advantageous in low-level detection of pulse signals, without the requirement for regulated bias current supplies and temperature chambers. These facts should be kept in mind when considering requirements for optical repeater circuits.

5-4. OPTICAL REPEATER CIRCUITS

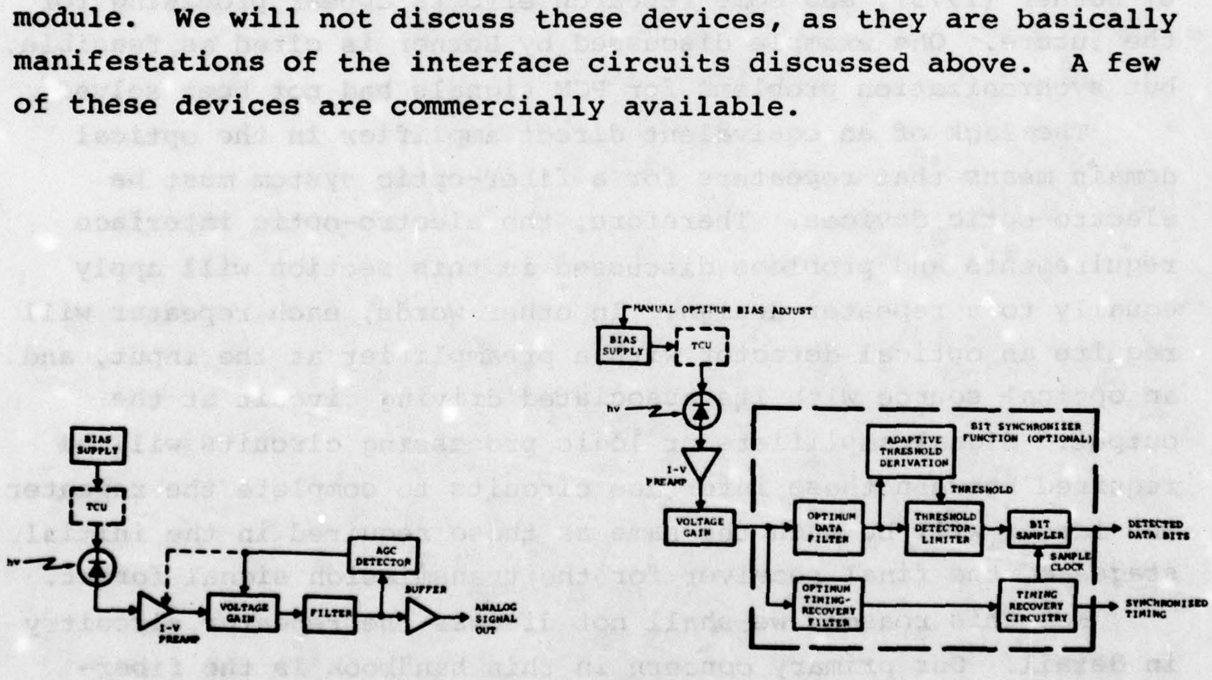
It was stated in the introduction to this chapter that there are no direct optical repeaters (optical amplifiers) practical at this time. Research on such devices, however, has been reported by Borner (1975), and some research efforts appear promising for the future. One example discussed by Borner is cited as feasible, but sychronization problems for PCM signals had not been solved.

The lack of an equivalent direct amplifier in the optical domain means that repeaters for a fiber-optic system must be electro-optic devices. Therefore, the electro-optic interface requirements and problems discussed in this section will apply equally to a repeater design. In other words, each repeater will require an optical detector with a preamplifier at the input, and an optical source with its associated driving circuit at the output. Signal amplifiers or logic processing circuits will be required between these interface circuits to complete the repeater. The latter will be much the same as those required in the initial stages of the final receiver for the transmission signal format.

For this reason, we shall not discuss the repeater circuitry in detail. Our primary concern in this handbook is the fiber-optic transmission mode as it applies to existing communication systems. The requirements for the electronic stages and circuitry between the two optical ports of the repeater will be dictated by the communication system, and its signal format. The detailed

circuitry will follow closely that of the given system, or actual system hardware may be adapted for use in the repeater stages. As an example of the requirements for both an analog and a digital system, Figure 5-17 (Casper, 1975) presents the receiver interface for each system in block-diagram form. The same elements shown in these diagrams will be necessary to the repeater, and the detected signal outputs will be used to drive another optical source for the continuing fiber. The circuits and techniques discussed in the previous sections are applicable to the two electro-optic interface ports.

Some manufacturers in the fiber-optics communication field are beginning to offer complete electro-optic modules. These include such devices as optical sources that are integrated with an electronic driving circuit in a single package. Optical detectors are also being furnished with an integrated preamplifier, and some with additional circuitry to form a complete receiver module. We will not discuss these devices, as they are basically manifestations of the interface circuits discussed above. A few of these devices are commercially available.



(a) Analog Interface (b) Digital Interface

TCU = Temperature Compensation Unit

Figure 5-17. Diagrams of typical analog and digital interface circuitry (Casper, 1975).

CHAPTER 6

OPTICAL FIBER LINK DESIGN AND PERFORMANCE PARAMETERS

6-1. INTRODUCTION

The procedure of selecting components for use in a specific application becomes rather complicated in an optical waveguide system because of the multitude of options available. One should always begin the design with a precise statement of needs and objectives to be met by the system. By defining all constraints at the outset and by giving proper allowances for fiscal and operational preferences, one can methodically consider each option in turn.

Unlike more conventional (i.e., metallic) guided-wave systems, optical waveguides, perhaps for the first time, introduce the possibility of operating either in a (1) power-limited or (2) a dispersion-limited regime. This is an important concept in the sense that the waveguide attenuation shows promise of being so low that signal amplitude will not be the limiting factor in defining allowed distance between transmitter and receiver or between repeaters. In the dispersion-limited regime, which is the appropriate regime for very low-loss fibers, the pulse distortion (overlap) becomes the limiting factor. A user who is faced with the design of a link or with the evaluation of a proposed link must understand the differences between the two regimes and know the crossover point, which defines the transition from one regime to the other. The dispersion-limited regime is quite tolerant of degradation of system components and, for that reason, an effort should be made to operate in that regime.

In the power-limited regime of operation, signal power is the factor that limits system throughput. In this case, component degradation can have a serious impact; the system, in this regime, is intolerant of decreased power levels since the throughput decreases exponentially with decrease in power into the detector.

In this chapter we will expand on these concepts and give guidelines to be used in evaluating the operation of a proposed

system or in designing a system to meet prescribed needs. The discussion will carry along the ideas associated with both power and dispersion limitations in a parallel fashion. The discussion will suppose that the reader is interested in designing a system. Those interested in evaluating a proposed system would ask themselves the same questions, cast in a slightly different format.

In the discussion which follows, we explicitly assume that the terminal devices (source and detector) have a switching speed that is fast enough to accommodate the signaling rate being contemplated. Product literature usually addresses this question since it is considered fundamental. If the device speed is questionable, then everything discussed in this section is academic. If the speed of this device is sufficient, then other design parameters are considered as discussed in the following. Comments on device speed were made in Chapter 2 of this document.

6-2. DESIGN PARAMETERS AND VARIABLES

The problem at hand demands that one consider the system in reverse order; i.e., one must begin by evaluating the demands on the receiver circuit end, which will in turn determine the requirements of the fiber and the optical source. The demands at the receiver will depend on several parameters which are fixed by system requirements. The key parameters are listed in the form of questions as follows:

1. What is the allowed bit error rate (BER)?
2. What is the total system length?
3. What is the proposed bit rate (R)?
4. Are there restrictions on available electrical power?
5. Are there severe economic constraints?
6. Must allowance be made for future expansion?

Items 1 through 3 are used to determine the required optical power at the detector for power-limited operation. They are also used to determine allowed pulse dispersion for operation in the dispersion-limited regime. The last three items are accounted for in component selection. In some cases, it might be advantageous to assign weighting factors to each of the last

items to permit more complete tradeoff evaluations in component selection. The manner in which each of the last three items is treated in the component decision process is a matter of style. However, there is no reason for allowing each item to be only qualitative. It can become quantitative if one is willing to establish a value criterion of each.

The suggested methodology next calls for consideration, in turn, of each of two possibilities: one should first go through the system (receiver to transmitter) assuming that operation is in the power-limited regime. Establishing the required transmitter characteristics under these assumed conditions, one next considers the dispersion-limited regime. Finally, the two are compared to determine which, in fact, is limiting the performance.

In tracking through the system, from receiver to source (the details of which are given in the following sections), one must consider, in turn, the detector characteristics, connectors and splices, the waveguide, and, finally, the source itself. At each juncture, the signal degradation (attenuation and distortion) is estimated, and the effects are summed to determine the resulting demands being made on the source. In the process, one must evaluate options in component selection. This can become a tedious exercise, but, in principle, can be done as thoroughly and methodically as desired. Rather rough rules of thumb can be used in some cases and in others an analytic expression might be available to assist in the evaluation phase.

In Appendix B, we present an example of a system design which requires many repeaters and a high bit-rate. In such systems, component reliability is important because repeater servicing is expensive. It is thus important that the required number of repeaters be minimized. Reducing the number of repeaters will improve the reliability of the total system.

Reliability is usually defined as the probability that a given device will perform in a specified way for a given time. In this sense, it is the chance that the device will "work" and it is based on a knowledge of certain parameters: (1) required

time of operation (also called mission time) and (2) a definition of successful operation. For purposes of this brief discussion, we restrict attention to normal operating failures of electronic and optical components. Such failures are assumed to occur at a constant rate, ψ, and they occur following the early or debugging failure cycle. Component failure in this normal operating cycle is random and infrequent. Reliability predictions are relatively easy to make during this operating cycle, for which the reliability, Φ, or probability of successful operation, for time t, follows an exponential law:

$$\Phi = \exp(-\psi t) = \exp(-t/m) \tag{6-1}$$

where

Φ = reliability = probability of successful operation for time t,

ψ = failure rate (constant),

$m = 1/\psi$ = mean time between failures = MTBF.

The mission time, T_m, is the time for which reliability must be maintained at value Φ. This definition of reliability (Machol, 1965, Section 33-2) is based on the failure of a component. A key entity in this definition, then, is the distribution of failures in the time domain (the parameter ψ). Such distribution is determined from a testing program which concentrates on failures which render the system inoperable. For our discussion, then, we need only be concerned with the fact that failures occur randomly and infrequently. Whatever the nature of that failure may be, it leads to failure of the system in the sense that successful operation is not realized.

When t = MTBF, Φ has a value of 0.368. A large value of Φ for time $t = T_m$ obtains if the MTBF is many times the mission time. For

$\Phi = 99\%$,

$m = 100T$.

In a long-haul system with N repeaters in series, reliability is

$$\Phi = \Phi_1 \Phi_2 \Phi_3 \cdot \cdot \cdot \Phi_N. \qquad (6\text{-}2)$$

where the nth repeater has reliability Φ_n. This expression assumes that failure of one repeater is independent of the failure of the others. According to this equation, the failure rate of the system is the sum of the failure rates associated with each repeater. If ψ is the same for each repeater, $\psi_n = \psi$ for all n, then the system reliability is given by

$$\Phi = \exp(-Nt/m). \qquad (6\text{-}3)$$

It is this harsh degradation of Φ with increasing N that is of concern in long-haul systems. As N increases, m must increase accordingly for fixed system reliability.

Redundancy can be used to circumvent some of the failures and thereby improve system reliability. There is a tradeoff involved in the use of such redundancy because, to be most effective, the alternate routes must be controlled by complex circuits. Nevertheless, there is usually a net gain in reliability through redundancy if one is willing to suffer the additional cost.

The improvement in reliability depends on how redundancy is used. The simplest technique is to duplicate all equipment and require the same information to be transmitted over each of the systems. This may not be desirable under a restricted power budget. A more sophisticated technique calls for the second system to begin operating only if the first becomes inoperable. This requires monitoring and logic circuitry, but conserves power. Combinations of these two themes are also possible with variations in cost and improvement in reliability.

When the product of bit-rate, R, and distance, L, between repeaters is large, it is advisable to give serious consideration to the use of single-mode waveguides. There are certain disadvantages associated with such waveguides, but the advantages are significant. In the final analysis, each user will have to

weigh carefully the consequences of deciding in favor of the single-mode version. This matter is discussed in Appendix A. It is also discussed in Appendix B, which is concerned with the analysis of a long-haul system design.

6-3. DESIGN METHODOLOGY

As noted above, a link design or evaluation problem begins with the evaluation of the required power budget. This includes the power required at the detector for the specified performance, all of the coupling, splicing and fiber losses, a margin for expected degradation, and finally a specification for the power that must be launched into the fiber waveguide at the transmit terminal. The power budget of the link is determined from the expression

$$P_s = P_d + L_c + L_s + L_f + L_m, \qquad (6\text{-}4)$$

where the terms are defined in Table 6-1. The power terms, P_s and P_d, are specified in dBm, and the loss and margin (L) factors are specified in dB (positive loss).

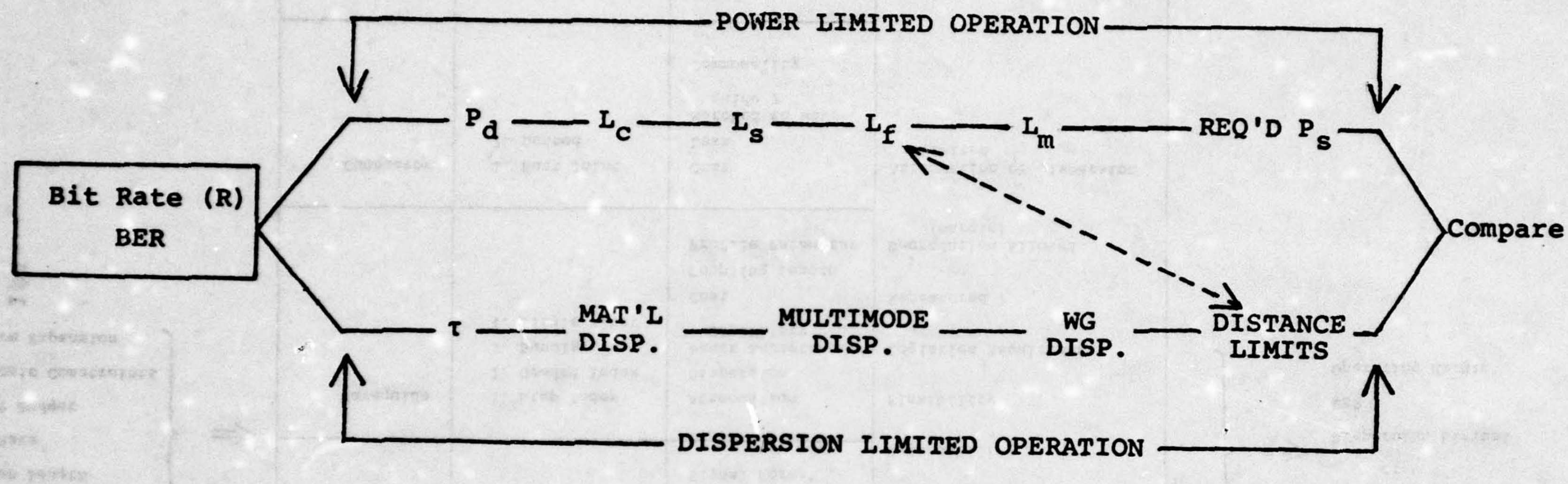
Table 6-1, shows symbolically, how one first specifies the desired bit rate and the required BER performance for the system, and then proceeds to determine the limiting factors. Table 6-2 shows some of the options available in selecting each component of the system and the variables associated with each. In the following sections, we will describe how each of the terms listed in Equation (6-4) is evaluated.

a. Power Limited Operation

In most practical cases of interest, limitations on system throughput arise because of limited optical power at the detector. This means that the losses suffered by the signal are sufficient to reduce the signal to a marginal magnitude. The methodology suggested in the preceding section calls for an evaluation of such limits, and then a confirmation by comparing these results with the results obtained for dispersion-limited operation.

Table 6-1

Flowchart for System Analysis



τ = PULSE WIDTH

P_d = REQ'D POWER INTO DETECTOR

L_c = CONNECTOR AND COUPLING LOSS

L_s = SPLICING LOSS

L_f = FIBER LOSS

P_s = SOURCE POWER

L_m = DEGRADATION MARGIN

Table 6-2

Parameters in System Analysis

Fixed Parameters

BER

System Length

Bit Rate

Power Budget

Economic Constraints

Future Expansion

⇒

Component	Options	Variables	Common Concerns
Optical Source	1. LED 2. LD (cw) 3. LD (limited duty cycle)	Lifetime Reliability Wavelength Rise Time Emitting Area Cost Emission Pattern Signal Format	Power Budget Cost Commonality Maintainability Expandability
Waveguide	1. Step Index 2. Graded Index 3. Bundle 4. Single Fiber	Attenuation Dispersion Power Acceptance Capability Cost Coupling Length Profile Parameter	Flexibility Logistics Requirements Repeatered ? Degradation Allowed (margin)
Connectors	1. Butt Joint 2. Lensed	Cost Loss Matched to wave-guide ? Commonality	Attenuation or dispersion Limited
Detector	1. Direct 2. APD	Cost Advantage (dB) of APD Power Budget NEP Value of Optimum gain	

⇒

Calculated Parameters

Loss Limited

or

Dispersion Limited

BER

Operating Margin

(1) Power required at the detector (P_d).

The manner in which power required to achieve a desired bit-error rate varies with bit rate depends on optical pulse shape and the receiver front-end design. A well-designed front end incorporates a high impedance preamplifier which tends to integrate detector output. The choice of detector material will depend on source wavelength since optical detector materials respond reasonably well only over a restricted wavelength range. In the vicinity of 0.85 µm, for example, silicon offers a quantum efficiency of 75% and dark current is quite low (see Chapter 2). A detailed analysis of the detector must also account for imperfect modulation and all thermal noise sources. The reader is referred to a comprehensive paper by Personick (1973) which covers the various facets of the problem. The results presented by Personick are for a special case, as defined below, but can be used to give insights into the more general case.

Following the work of Personick, we consider, for purposes of illustration, the following case:

BER: 10^{-9}

Detector: silicon; quantum efficiency = 75%

Excess detector noise exponent: 0.5

Dark current before gain: 100×10^{-12} amperes (A)

Total shunt capacitance across detector: 10 pF

Input resistance: 10^{6} ohms (Ω)

Optical pulse received: half duty cycle rectangular pulse

Equalized output pulse: raised cosine pulse.

With these assumptions, the required power at the detector is

$$P_d = \begin{cases} 3.25 \times 10^{-8} \left(\frac{R}{R_o}\right)^{3/2} \text{ watts, no gain} & (6\text{-}5) \\ 1.64 \times 10^{-9} \left(\frac{R}{R_o}\right)^{7/6} \text{ watts, optimum gain.} & (6\text{-}6) \end{cases}$$

These expressions are based on an exponential decrease of allowed bit rate, R, with distance, L.

In these equations, R_o is the reference bit rate of 25 Mb/s and P_d is the power required at the detector. Optimum avalanche gain is defined as the gain required to minimize the required optical energy in an "on" pulse. The minimum optical power obtains when the pulses are very narrow. If pulse width is not small, there is a penalty, in dB, which the system must pay. The optimum value of gain, G_{opt} varies as $R^{1/3}$ and is given by Equation (6-7):

$$G_{opt} = G_r \left(\frac{R}{R_o}\right)^{1/3} \tag{6-7}$$

where the reference optimum gain G_r is 57, according to Personick (1973). The results given in Equations (6-5) to (6-7) are felt to be valid over the range 5 to 300 Mb/s.

Equations (6-5) through (6-7) can be used to begin the process illustrated in Table 6-1 of the preceding section. If we assume a bit rate of 25 Mb/s, for example, the required detector power is -44.88 dBm or 32.5 nanowatts (no gain) or -57.85 dBm or 1.64 nanowatts (with optimum gain of 57). The variations given in Equations (6-5) - (6-7) are shown graphically in Figure 6-1(a). The required power and value of optimum gain change only slowly with BER, as seen from Figure 6-1(b), which also shows the advantage, in dB, of optimum gain over unity gain. Referring to Table 6-1, we now have two values of P_d: one with unity gain, one with optimum gain. Whether or not any gain is required will depend on system loss.

(2) Coupling loss (L_c).

The coupling loss (L_c of Table 6-1) at the source and the receiver ends depends on the relative size of the components and on the alignment technique. The total coupling loss is made up of several factors discussed below.

If a fiber bundle is contemplated as the transmission line, one must include the packing-fraction (PF) loss, which is suffered at the input end and at each splice. Packing-fraction loss is suffered because only the optical power incident on the core is

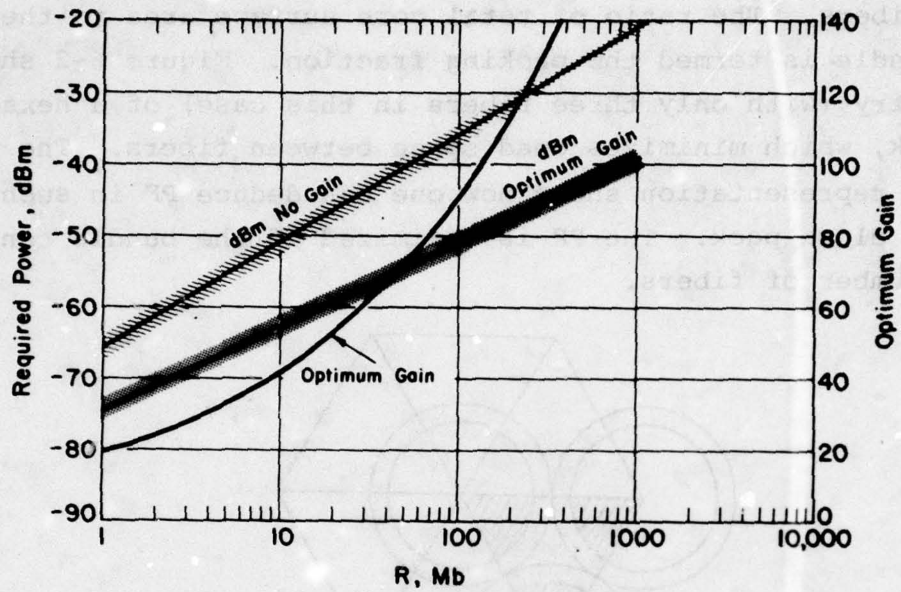


Figure 6-1(a). Variation of power requirements and optimum gain.

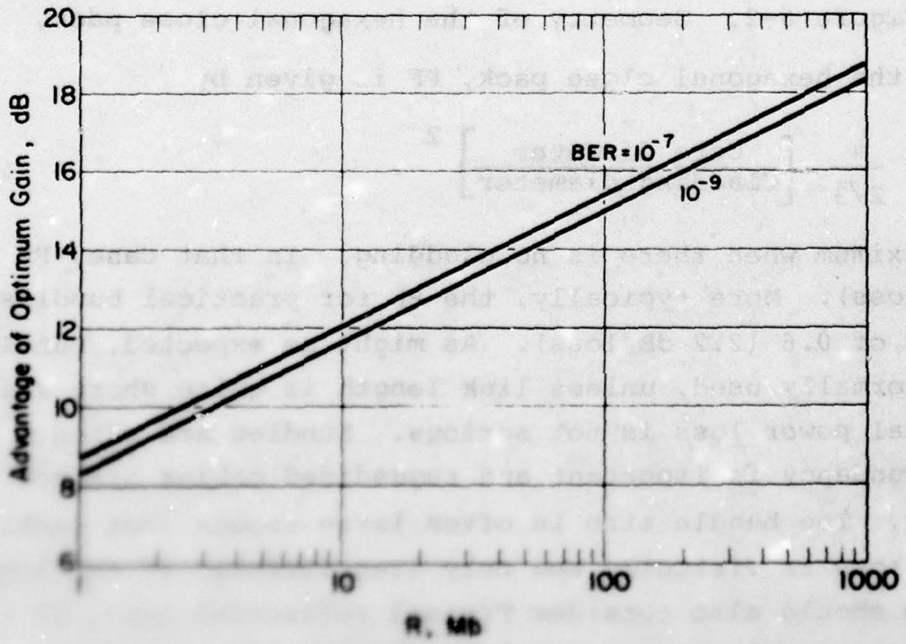


Figure 6-1(b). Advantage of optimum gain.

effective. The end of the fiber bundle, however, exposes not just core surface but also cladding surface and empty space between fibers. The ratio of total core surface area to the area of the bundle is termed the packing fraction. Figure 6-2 shows the geometry (with only three fibers in this case) of a hexagonal close pack, which minimizes dead space between fibers. The geometric representation shows how one can deduce PF in such a hexagonal close pack. The PF is maximized if the bundle contains a prime number of fibers.

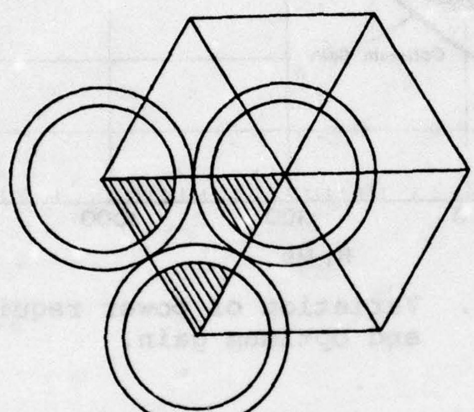


Figure 6-2. Geometry of the hexagonal close pack.

For the hexagonal close pack, PF is given by

$$PF = \frac{\pi}{2\sqrt{3}} \left[\frac{\text{Core diameter}}{\text{Cladding diameter}}\right]^2 . \qquad (6\text{-}8)$$

and is maximum when there is no cladding. In that case, PF = 0.91 (0.4 dB loss). More typically, the PF for practical bundles is on the order of 0.6 (2.2 dB loss). As might be expected, bundles are not normally used, unless link length is quite short and the optical power loss is not serious. Bundles are often used where redundancy is important and ruggedized cables are not necessary. The bundle size is often large enough that packing fraction loss is virtually the only loss suffered at the input end. One should also consider Fresnel reflection loss, if appropriate, in determining the total value of L_c.

Fresnel reflection losses are suffered whenever the optical path includes an abrupt change in refractive index. The reflection can be thought of as being due to a change in wave impedance and is akin to the reflection which results in a coaxial cable when the characteristic impedance of the cable changes abruptly. A reflection occurs thus when light enters a fiber and when light leaves a fiber, unless steps are taken to match the refractive index via an index matching fluid. For normal incidence on the end of a polished fiber, the fraction of incident power that is reflected is $(n_1-n_o)^2/(n_1+n_o)^2$ where n_1 and n_o are the refractive indices of the core and of free space, into which the wave is being transmitted. If $n_1 = 1.5$ and $n_o = 1$, which is typical, about 4% of the incident power is reflected (0.18 dB loss).

Another component of the total coupling loss, L_c, is the loss encountered in coupling into the detector. The major contribution to such loss is the mismatch in surface area if the fiber size (or bundle size) is greater than the size of the detector. Other losses include loss due to reflection from the end of the fiber, that due to angular or lateral misalignment, and to other geometric-type faults. A liberal rule of thumb would be to allow 1 dB (no more than 2 dB) loss in coupling into the detector.

The loss encountered in coupling from the source into the fiber is a function of geometric match between source and fiber (or fiber bundle) and the source radiation pattern. These factors were discussed in Chapter 2, dealing with components. The geometric terms include area match and angular or lateral mismatch as well as longitudinal separation between source and fiber. The loss introduced by the source-to-fiber separation is a function of the radiation pattern.

The source radiation pattern is an important (usually dominant) factor in determining loss at the input. Most of the optical energy falling within the numerical aperture of the fiber will be collected by the fiber. Figure 6-3 shows conceptually the amount of light energy that falls outside the acceptance angle of the fiber and is lost. The amount of power incident on the end of the fiber is calculated by knowing the radiance of the

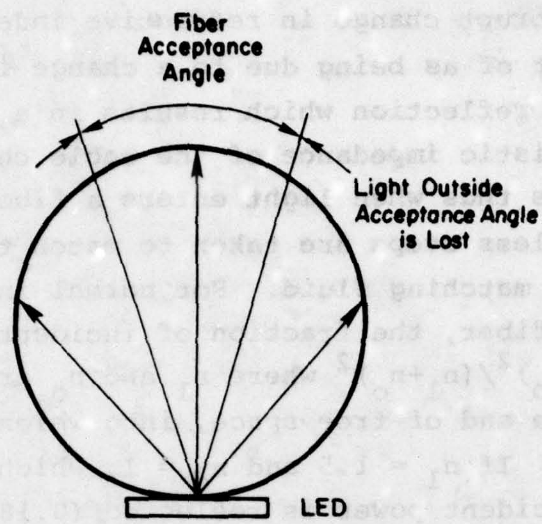


Figure 6-3. Lambertian emission and finite acceptance core.

source (N) as a function of position and as a function of angle (ϕ) between the normal to the emitting surface and a line to the observation point. For many practical applications, the radiation pattern varies as $(\cos\phi)^m$ where m = 1 for many LED's and m can be as great as 15 for laser diodes (LD's)(the basic structure, with no lenses). In the case of a Lambertian source (m = 1), the total power (P_T) in watts incident on the core of numerical aperture (NA) is

$$P_T = P_o\,(NA)^2 \qquad (6\text{-}9)$$

where

$$P_o = A_s \pi N_o\,, \qquad (6\text{-}10)$$

and A_s is the emitter surface area in m^2, and N_o is the radiance (watts/steradian/m^2) along the optical axis of the source (ϕ = o). When m≠1, the expression (6-9) becomes

$$P_T = P_o\left[1 - (\cos\phi)^{m+1}\right], \qquad (6\text{-}11)$$

where ϕ becomes the critical angle of the associated fiber (cf. Chapter 2), and P_o is the total power emitted by the source.

Clearly, a narrow radiation pattern (large m) allows better coupling to the fiber. In practice, one must consider both planes of the emission pattern and integrate to determine coupling loss. If the fiber core area is less than the area of the emitting surface, the power coupled into the fiber is reduced in proportion to the ratio of the areas.

The relationship between power out of the source and power collected by the fiber is the principal factor in calculating coupling loss. Clearly, with other things being equal, a large NA is advantageous in order to collect as much power as possible in the fiber.

The radiation pattern of an optical source is subject to some variability. The optical axis may, in fact, be slightly misaligned relative to the expected axis (usually the mechanical axis). A prediction of the expected loss due to optical axis misalignment should be based on measured statistical data rather than the mechanical alignment for any particular radiator. Figure 6-4(a) shows the expected additional loss owing to such angular misalignment. The loss is relatively insensitive to the misalignment, and as much as 5° can be tolerated rather easily.

If the source is not butted directly against the fiber, there will be an additional loss because of the spread of the radiation beam with distance. These losses can usually be reduced with lenses. Figure 6-4(b) shows the loss one should expect with such separation. Note that nominal separations are tolerable. If the fiber being contemplated has a graded refractive index, the power collecting ability is less than it would be for a step-index fiber. This is shown in Figure 6-5, which shows the power as a function of the profile parameter, α, (discussed in Appendix A) relative to the power launched into a step-index fiber; i.e., the curve approaches 1 as α becomes large, which corresponds to the step-index fiber. The assumed source is Lambertian (see glossary) and all other losses are ignored in this figure. Note that the parabolic profile (α=2), which has highly desirable propagation characteristics, suffers a loss of

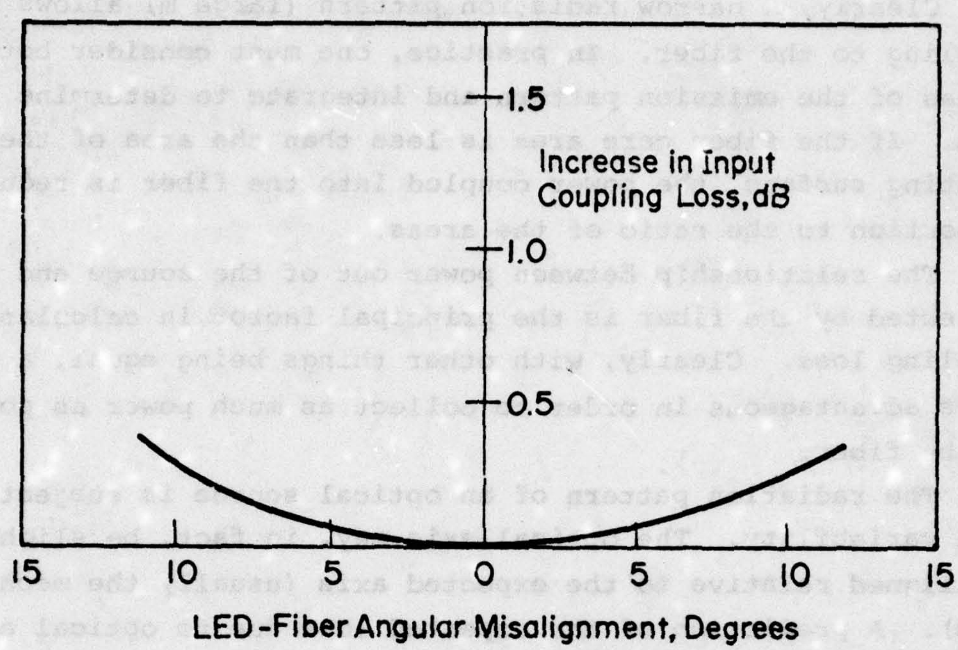


Figure 6-4(a). Loss due to angular misalignment.

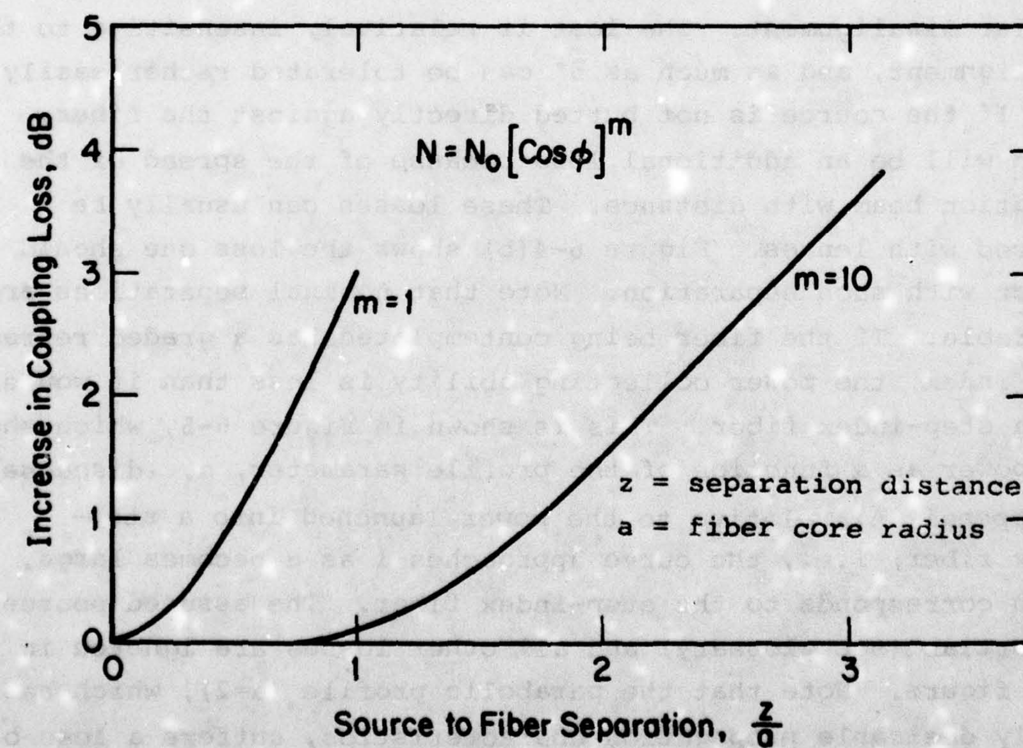


Figure 6-4(b). Loss due to fiber separation.

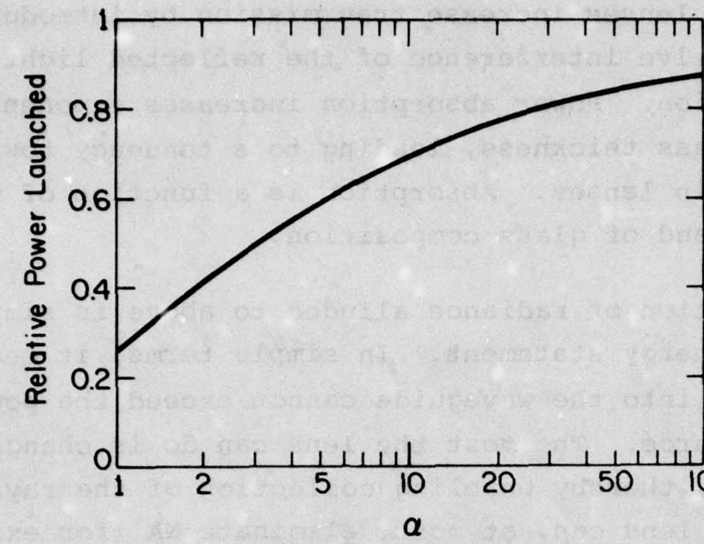


Figure 6-5. Power launched into graded index fiber, relative to a step index fiber.

nearly 4 dB relative to the step-index profile. Of course, sources with a more directive radiation pattern would fare better in effective launch of optical power.

It is often advantageous to use lenses to focus the light rays emanating from a source in order to improve coupling into the fiber. In such cases, one must know the intensity of light transmitted through the system of lenses. Every light source has a radiation pattern, which describes the radiation intensity variation with direction. A system of lenses will increase the light-gathering ability of a fiber or a bundle by changing the direction of the light rays to bring them within the acceptance angle of the fiber. In using lenses, the design engineer must realize that, while power coupled into the waveguide may increase, radiance is conserved; i.e., radiance cannot be increased through the use of lenses; it can only be diminished. The diminished radiance is due to two distinct causes:

1. Reflection. There is power loss of about 4% due to reflection from an untreated surface. This can be reduced through the use of index-matching jackets.

Treated lenses increase transmission by introducing destructive interference of the reflected light.

2. Absorption. Power absorption increases exponentially with glass thickness, leading to a tendency toward only thin lenses. Absorption is a function of wavelength and of glass composition.

The conservation of radiance alluded to above is simply a conservation-of-energy statement. In simple terms, it means that the power coupled into the waveguide cannot exceed the power emitted by the source. The most the lens can do is change the direction of rays, thereby enabling collection of the rays by the fiber. Thus, the lens can, at most, eliminate NA (for example) as a multiplying factor in the expression for P_T in equation (6-9).

The conservation of radiance principle is a source of confusion, and it is sometimes erroneously assumed that lenses (or a tapered rod) can do more than this law of physics would allow. Radiance (watts/m^2/sr) is the power emitted per unit incremental area per unit incremental solid angle, in the direction of the solid angle, which is normal to the surface area. A lens will translate an object space (the source, for example) into an image space. The conservation of radiance principle states that the radiance in the image space cannot exceed that in the object space. If the fiber core area, A_f, is less than the source area, A_s, the coupling efficiency contains the ratio A_f/A_s. If $A_f > A_s$, a lens can improve coupling. If the source emitting area is larger than the fiber core, any decrease of angular divergence accomplished by the lens, is offset by a corresponding magnification of source dimensions, precluding a net increase in coupling efficiency.

A cylindrical lens can be used to improve coupling between the elliptic pattern of a stripe geometry laser diode and the circular geometry of a fiber. The resulting improvement is especially important in coupling to single-mode waveguides, which have small core diameters.

(3) Splicing loss (L_s).

An in-line splice of a single fiber will introduce losses if the axes of the two fibers to be joined are not perfectly aligned. Figure 6-6 shows the expected loss due to such misalignment as a function of the normalized lateral displacement, d/2a, where a is again the core radius of the fiber. Note that losses are quite sensitive to lateral displacement of the fiber axes.

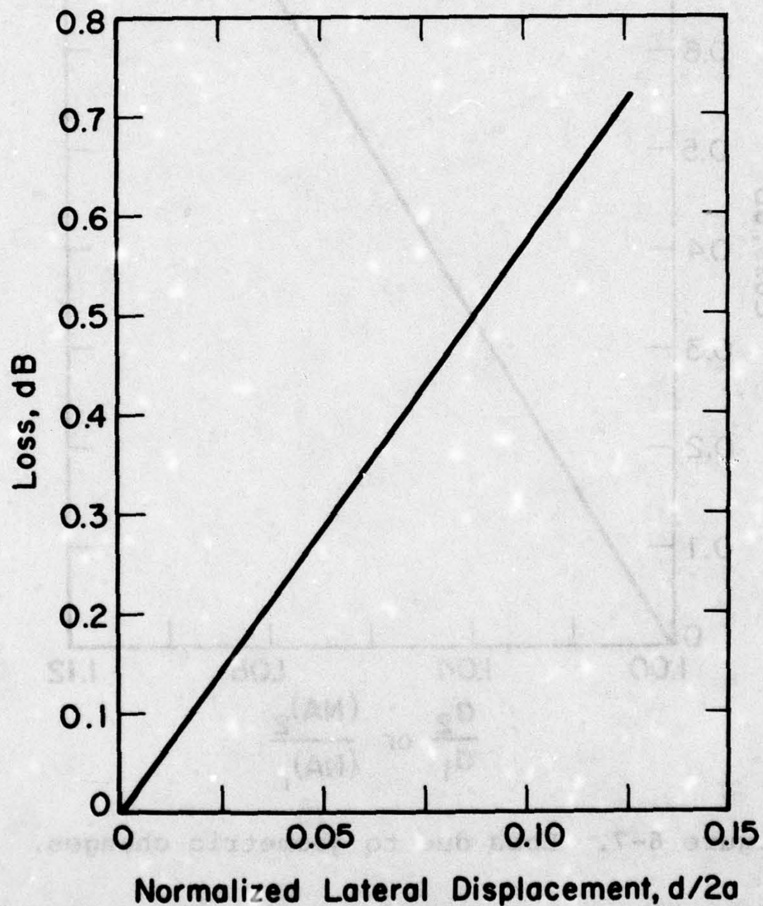


Figure 6-6. Loss due to lateral displacement of fibers to be spliced.

The core radius of a fiber is subject to variation, even in the most refined manufacturing process. If two fibers of different core radii and/or a different NA are to be joined, additional loss will be introduced. These two losses are additive, and an

in-line splice may, in fact, introduce loss due to each of the effects. Figure 6-7 shows the expected additional loss due to the mismatch between the two fibers (subscripts 1 and 2).

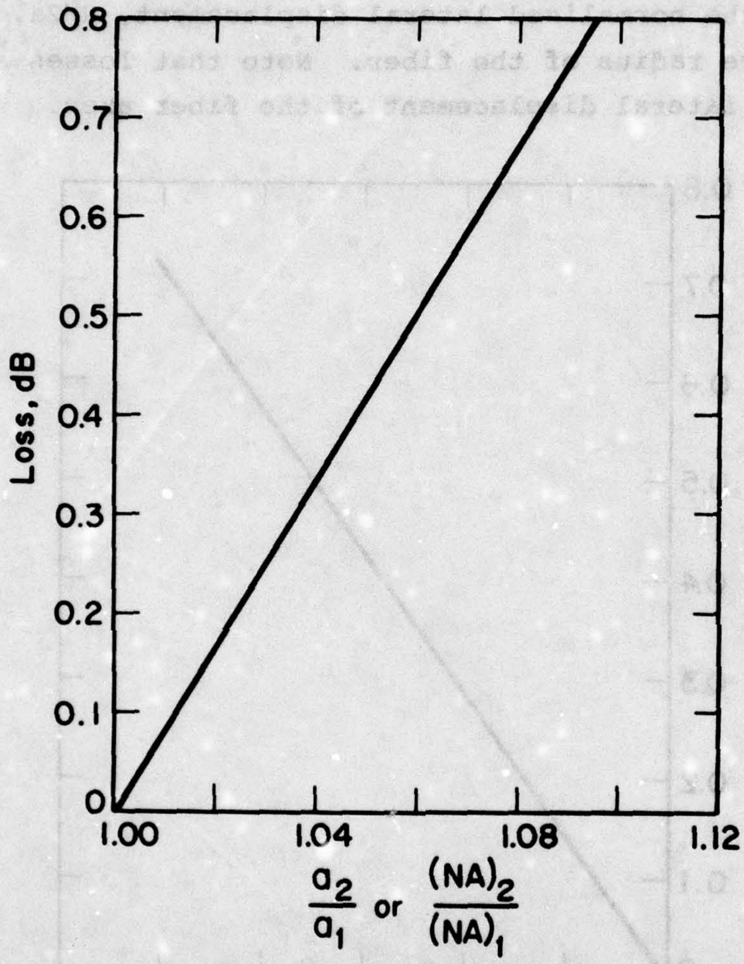


Figure 6-7. Loss due to geometric changes.

An in-line splice of two graded-index fibers will introduce loss if the two fibers have different profiles. The profile parameter, α, is a measure of the refractive index variation with distance from the fiber axis (see Appendix A).

Figure 6-8 shows the expected loss, in dB, for an in-line splice of two fibers having different values of α; subscripts 1 and 2 again refer to the two fibers. As a point of interest, we

call attention to the fact that a splice between a parabolic-profile fiber and a step-index fiber ($\alpha=\infty$) introduces a 3-dB loss. The tendency for such loss can be inferred from Figure 6-8 by noting the asymptote of the curve labeled $\alpha_1=2$ (parabolic profile) for large α_2.

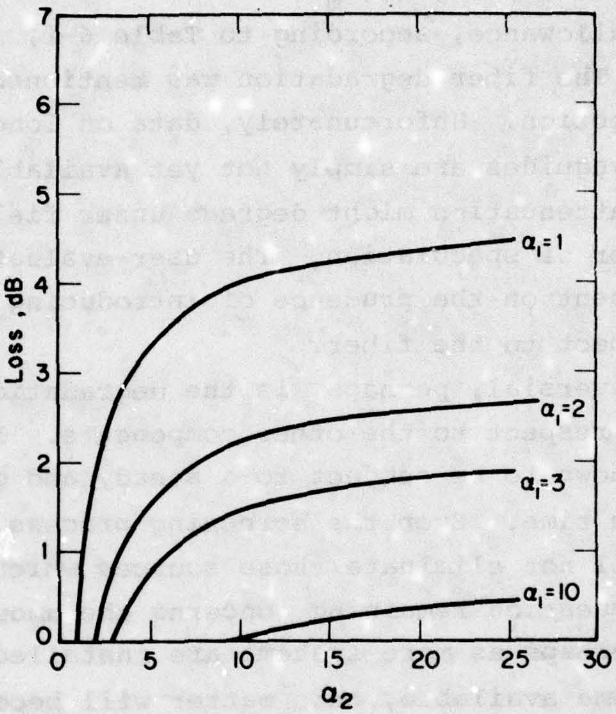


Figure 6-8. Loss due to profile changes.

(4) Fiber loss (L_f).

The preceding sections considered the sources of loss due to coupling and splices, including coupling loss at the input and at the output ends. Another major source of system loss is, of course, the loss due to fiber attenuation. Various grades of fiber are available today and the loss, γL (dB), depends on the quality of fiber being contemplated (i.e., attenuation factor γ) and the length of the fiber between repeaters (L). In repeaterless systems, L is the fiber length between transmitter and receiver. In considering such loss, allowance must be made for at least a nominal amount of degradation if the fiber is subjected to harsh field conditions. Frequent handling or physical abuse

may lead to an increased attenuation constant because of increased microbending loss. Graded index fibers are less tolerant of physical abuse and microbending loss is more easily induced in such fibers.

(5) Degradation margin (L_m).

The final allowance, according to Table 6-1, is for degradation margin. The fiber degradation was mentioned briefly in the preceding section. Unfortunately, data on long-term stability of fiber waveguides are simply not yet available. The manner in which fiber attenuation might degrade under field conditions is still a matter of speculation. The user-evaluator will have to make a judgement on the prudence of introducing a degradation margin with respect to the fiber.

Less controversial, perhaps, is the degradation margin called for with respect to the other components. In particular, the source is known to be subject to a steady and graceful degradation with time. Even the screening process imposed by most vendors will not eliminate those sources which degrade with use. The only question remaining concerns the amount of degradation. Perhaps as more systems are installed and degradation data become available, this matter will become more clear. The recommendation here is to allow a degradation of from 3 to 6 dB. Detectors are known to be quite stable but the use of an APD, for example, depends on the use of a stable power supply. As the bias voltage is subject to gradual fluctuation, so is the gain. Thus, it is prudent to allow some margin even there. Frequent connect-disconnect cycles in splices will also introduce some degradation. This is not likely to be a source of major loss in most systems, however.

(6) Required source power (P_s).

Having evaluated the losses in the system, and knowing the power required at the detector, P_d, we are now in a position to determine, P_s, the required power out of the source. That power, in dBm, was given in (6-4) and is repeated here for convenience as (6-12):

$$P_s(\text{dBm}) = P_d(\text{dBm}) + L_c + L_s + L_f + L_m . \qquad (6\text{-}12)$$

Here, the last 4 terms are the loss factors in dB that have been discussed in the preceding sections. The value of P_d is determined from Equations (6-5) or (6-6), or a modification of one of them. In practice, Equation (6-12) will be considered several times to determine P_s under each of several conditions. If P_s is greater than can reasonably be expected for the source under consideration, the equation can be reworked with revised repeater spacing and/or associated revised fiber loss (L_f). In the case of very low-loss fibers, the number of splices (and, correspondingly, the value of L_s) may be determined by the length of fiber cable that can be drawn in one piece.

The important information coming out of the evaluation of Equation (6-12) is the total length, L, allowed for the fiber being considered. It is that value, L, that must be compared to the maximum value of L allowed under dispersion-limited conditions. The actual allowed length of fiber between repeaters will be the least of the two.

The reader will note from this discussion and from the suggestions of Tables 6-1 and 6-2, that the evaluation of Equation (6-12) may have to be done several times, because of the options and the variables that must be considered. Note that there are several options available for each component. The operational characteristics of each must be taken into account in the evaluation of Equation (6-12).

b. Dispersion-limited Operation

According to the plan outlined in Table 6-1, the second phase of the two-phase evaluation process calls for the determination of allowed terminal spacing when operation is dispersion limited. In this regime of operation, the pulse amplitude is assumed to be above the noise level, but the spread of the signaling pulse, due to dispersion, is sufficient to render questionable the presence or absence of a pulse. In this regime

of operation, degradation of bit rate is algebraic in L, rather than exponential, as it is in the power-limited regime (see Equations (6-5), (6-6)). Thus, in the dispersion-limited regime, the allowed bit rate varies as

$$R = \kappa L^{-\xi} , \tag{6-13}$$

where ξ is not greater than unity. The value of ξ depends on certain fiber waveguide parameters and on the dominant cause of dispersion. The value of the multiplying constant, κ, is determined by the optical properties of the waveguide. There are many complicated factors that impact on the value of κ and ξ and those factors are difficult to sort out and to analyze. A practical approach would be to first assume the most pessimistic estimate of dispersion. If under that assumption, the system is determined to be power limited, a more conservative (and realistic) estimate of dispersion is not necessary. If otherwise, a more refined approach is called for. There are several causes of dispersion (as discussed below) but usually only one cause need be considered because it dominates.

There are several causes of pulse distortion, most of them related to the fact that the phase and group velocities of the signal depend on frequency. Modal dispersion is an exception. If the fiber acts as a single-mode waveguide (which is desirable for systems requiring a large range-bit-rate product), signal distortion arises from two sources: First, the glass material from which the fiber is drawn has frequency-dependent optical properties; i.e., the refractive index of the core and of the cladding is a function of frequency. This is known as material dispersion. Second, the group velocity of the mode is dependent on frequency even in the absence of material dispersion. This is known as waveguide dispersion, and it can be thought of as being due to the fact that the electrical dimensions of the waveguide change with frequency.

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In multimode waveguides, dispersion arises because, in addition to the above, each short pulse (in the time domain) generated by the optical source is launched into many guided modes; thus, each short pulse splits into a sequence of pulses that arrive at the receiver at different times. The spread in arrival times depends on the nature of the refractive-index profile of the waveguide. It is this spread in arrival times of the sequence of pulses that is interpreted (by the detector) as a broad, single pulse; this is the dominant cause of pulse distortion in heavily overmoded waveguides.

This pulse distortion in overmoded waveguides can be reduced in either of two ways: first, mode coupling can be introduced to cause an averaging of group velocity over the spectrum of guided modes or, second, a fiber having a graduated, continuous refractive-index profile can be used. The latter is the graded index fiber, as previously explained, where the refractive index changes gradually from its maximum value on the axis of the fiber to a slightly lower value at the core-cladding boundary. If properly constructed, such a graded-index fiber can cause all modes to have nearly the same group velocity and a single narrow pulse arrives at the detector. Several recent studies indicate that fibers having a parabolic (or a near-parabolic) index profile will have bandwidths that are 2 to 3 orders of magnitude greater than the bandwidth of a comparable step-index fiber (see Appendix A).

Unfortunately, proper analysis of the potential of a fiber requires the introduction of yet another dispersive term, namely, a profile dispersion term. This term accounts for the fact that the profile shape also changes with frequency, since the core and cladding materials are different and their respective dependence on frequency is not identical. Each of these sources of dispersion is discussed in the following section.

(1) Material dispersion.

A contributor to dispersion, common to all fiber waveguides, is that due to the material. This is the fundamental dispersive

term since it remains after all other causes have been removed. Even in the single-mode waveguide, material dispersion must be accounted for, although it is sometimes negligible.

For a plane wave traveling in an infinite medium of refractive index n, the group delay, τ, per unit length, is

$$\tau = \frac{1}{c}\left(n - \lambda \frac{dn}{d\lambda}\right), \tag{6-14}$$

where λ is the wavelength (cf. Appendix B). If a pulse of spectral width $\Delta\lambda$ propagates through the medium, the pulse width $\Delta\tau$, after unit length, will be

$$\Delta\tau = \frac{d\tau}{d\lambda}\,\Delta\lambda \quad . \tag{6-15}$$

The received pulse width will depend upon the refractive index of the medium, the spectral width $\Delta\lambda$, and the length of the transmission path. Also, from Equation (6-14) we find

$$\Delta\tau = -\frac{\lambda}{c}\,\frac{d^2n}{d\lambda^2}\,\Delta\lambda , \tag{6-16}$$

per unit length. The terms which multiply $\Delta\lambda$ on the right hand side of Equations (6-15) and (6-16) are known as material dispersion, since it is those terms which determine the effect of material variability of pulse spread. If the refractive properties of the optical material are known, Equation (6-16) can be used to determine the received pulse width, knowing $\Delta\lambda$ and the length of the fiber. A study performed in 1964 (Malitson, 1965) is often quoted as a comprehensive and reliable source of such data. In that study, the refractive index of high-purity, optical quality fused silica is given as a function of wavelength, based on controlled measurements at 60 wavelengths over the spectral range 0.2139 to 3.7067 μm. The results of these measurements could be used to evaluate Equation (6-16), using a modern programmable calculator. It must be noted, however, that the dopants that are added to pure fused silica to increase its refractive index, cause changes in material dispersion. Certain dopants affect the dispersive properties more profoundly than others.

Another approach would call for the direct measurement of $d\tau/d\lambda$ for the optical material being considered. Reliable data of this type have been provided by Payne, et al., (1975) that are applicable to modern low-loss fiber waveguides. For example, Figure 6-9 shows the material dispersion measured for two different materials over a range of optical wavelengths. Note that the dispersion is given in ps/nm, per unit length. Measurements have shown that material dispersion for compositions used in modern low-loss waveguides exhibit very low values at wavelengths near $\lambda = 1.2\ \mu m$ (Malitson, 1965; Fleming, 1976). This is an important result for future systems that may operate in the longer wavelength region. It is companion to the lower attenuation factors found for fibers at the longer wavelengths (Chapter 2), and is also important when single-mode fibers are considered.

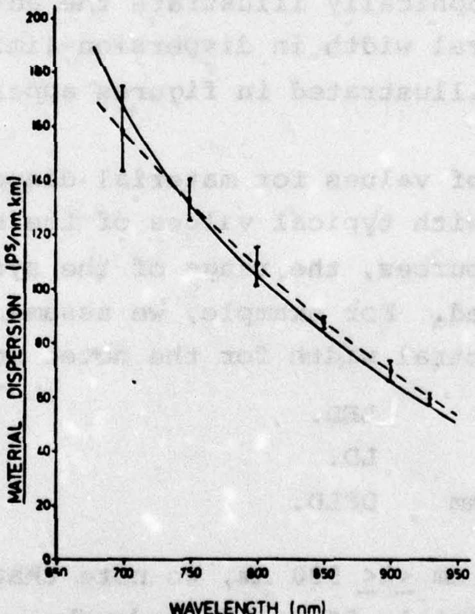


Figure 6-9. Material dispersion for phosphosilicate glass (broken line) and fused silica (solid line).

Figure 6-9 shows how material dispersion varies as a function of λ for phosphosilicate glass (broken line) and fused silica (solid line) using Malitson's data. Note the decrease in the value of dispersion with increasing λ, illustrating the trend noted above. Similar results are shown for other glasses by Fleming (1976). The results shown in Figure 6-9 have been used to plot the material dispersion for fused silica (the most commonly used glass) as a function of $\Delta\lambda$ in Figure 6-10. The parameter of the various curves is the wavelength of the optical source. The reader is cautioned that these data do not reflect the other (and often important) dispersion results due to waveguide and multimode factors. Also shown in the figure is the range of typical values of source spectral widths for laser diodes and for LED's. Note also the low range of dispersion that should be attainable with the distributed-feedback laser (DFLD), which may have a source spectral width of less than 0.5 nm. These observations graphically illustrate the advantage of using a narrow source spectral width in dispersion-limited design. The advantage is further illustrated in figures appearing in Appendix B.

Using the range of values for material dispersion shown in Figure 6-9, together with typical values of the spectral width for various optical sources, the range of the system dispersion factor can be estimated. For example, we assume the following general ranges in spectral width for the noted sources:

1.	20 to 40 nm	LED.
2.	2 to 4 nm	LD.
3.	0.2 to 0.4 nm	DFLD.

Over the range of 700 nm $\leq \lambda \leq$ 900 nm, we note that the material dispersion is approximately 50 to 150 ps/nm/km. Thus, the pulse spread ($\Delta\tau$) due to material dispersion alone, will generally be within the following ranges:

1.	1 ns/km $\leq \Delta\tau \leq$ 6 ns/km	LED.
2.	0.1 ns/km $\leq \Delta\tau \leq$ 0.6 ns/km	LD.
3.	0.01 ns/km $\leq \Delta\tau \leq$ 0.06 ns/km	DFLD.

The significance of these values is most relevant to future systems, where perhaps single-mode fibers can be used with either LD or DFLD sources to meet long-haul system requirements. Considerations for such systems and appropriate fiber choices are discussed in Appendix A.

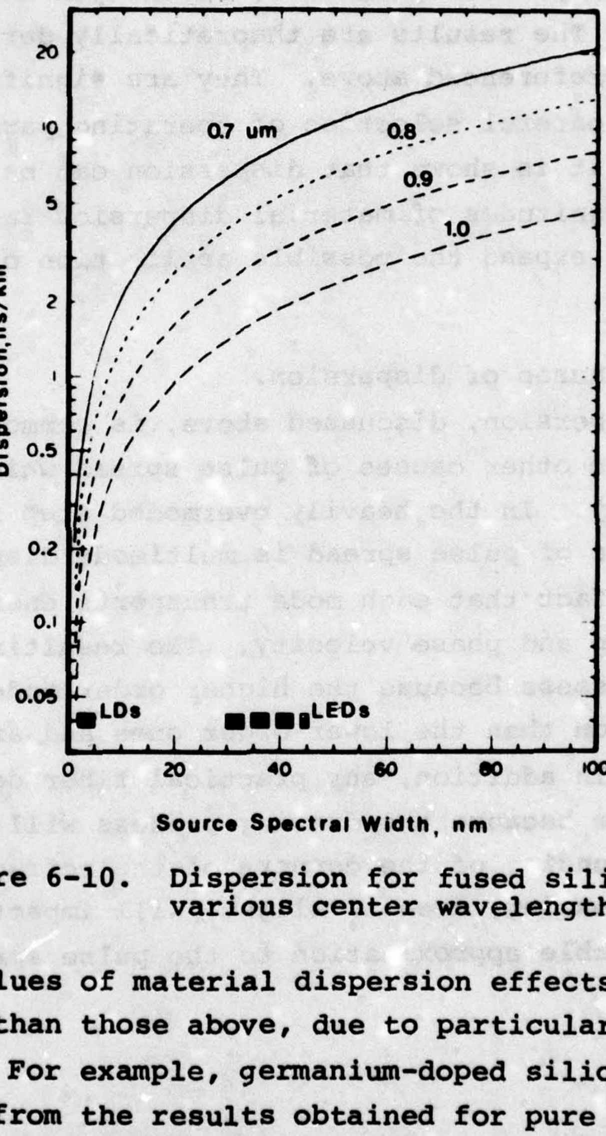


Figure 6-10. Dispersion for fused silica for various center wavelengths.

Actual values of material dispersion effects can be considerably higher than those above, due to particular dopants used in the fiber. For example, germanium-doped silica departs significantly from the results obtained for pure silica. Some dopants, however, such as P_2O_5 will serve to modify the refractive index without significantly affecting the dispersive properties of silica.

Material dispersion can be significant in the application of graded-index fibers. These results can be gleaned from the discussions given in Appendices A and B. Appendix A contains a discussion of the general dispersion properties of multimode fibers. The dependence of the dispersion affects of the graded-index fiber on the profile parameter, wavelength and source width are illustrated. The results are theoretically derived, based on the data sources referenced above. They are significant in the sense that, with careful selection of operating parameters and fiber materials, it is shown that dispersion can be reduced toward the low magnitudes of material dispersion factors. Such detailed analyses expand the possible application of fibers for long-haul systems.

(2) Other causes of dispersion.

Material dispersion, discussed above, is common to all waveguides. There are other causes of pulse spread which depend on the fiber geometry. In the heavily overmoded step index fiber, the dominant cause of pulse spread is multimode dispersion, arising from the fact that each mode transports energy and each has a unique group and phase velocity. The resulting pulse spread is difficult to assess because the higher order modes suffer greater attenuation than the lower order ones and are not excited as efficiently. In addition, any practical fiber does not have a step index profile because the drawing process will invariably introduce some rounding of the corners of the refractive index profile. This rounding, even if slight, will impact on pulse spread. A reasonable approximation to the pulse spread for step index fibers is

$$\Delta\tau \cong \frac{Ln_1\Delta}{c2\sqrt{3}} \qquad (6\text{-}17)$$

where n_1 is the refractive index of the core and Δ is the contrast term (Chapter 2). Typical values predicted from this expression are on the order of 20 ns/km. Note, then, that this term is much larger than that expected from material dispersion (cf. Figure 6-10).

If the fiber is multimode graded index, the pulse spread will depend on how well the profile of the refractive index has been patterned. The total dispersion (aside from material dispersion) includes contributions due to intermodal spread and due to profile dispersion. The first can be substantially reduced by using a precisely defined profile; the second is due to the fact that contrast (Δ) is a function of wavelength. There is an intricate relation between the various contributors and a more complete discussion is relegated to Appendix A. For purposes of this chapter, we state that the pulse spread is proportional to Δ^2, rather than to Δ, as was the case for the step index fiber. The reader will recall that Δ is small (usually less than 0.01) so the Δ^2 variation reduces dispersion. Graded index fibers with finely tuned refractive index profiles have the potential of causing much less pulse spread, approximately as follows:

$$\Delta\tau \cong \frac{Ln_1\Delta^2}{c20\sqrt{3}} , \qquad (6\text{-}18)$$

where c is the speed of light in m/s and L is in meters. This expression encompasses approximations which are discussed in Appendix A.

Finally, when a single mode fiber is envisioned, the user can expect a very attractive pulse spread. Of course, single mode operation involves difficulty in splicing and coupling and those aspects will impact on the power budget. In the single mode case, it is most convenient to consider all dispersion terms at once (including material dispersion). The results are given in Appendix A. For purposes of this chapter, we note that pulse spread is given, approximately, by

$$\Delta\tau = \frac{1}{c} D_1 \ (\Delta\lambda) \qquad (6\text{-}19)$$

where $(\Delta\lambda)$ is the source spectral width and D_1 depends on the operating wavelength and the materials used in the fiber (cf. Appendix A). At a center wavelength of 900 nm, D_1 is on the order of 10^{-5} if $\Delta\lambda$ is given in nanometers. The cautious reader will consult Appendix A to determine guidelines appropriate to this expression.

(3) Summary of dispersive properties of fibers and their effects.

The preceding two subsections have summarized the effects of the finite bandwidth of the fiber. Three types of fiber waveguides were considered: step index multimode; graded index multimode; and single mode. An approximate expression for pulse spread for each was given in Equations (6-17), (6-18), and (6-19), respectively.

We note immediately that the specifications provided by the vendor often do not include all the parametric values. For example, we note that Δ and/or $(\Delta\lambda)$ are required to evaluate pulse spread. Yet these values are not always given in the specification sheets. Is is not known, for example, what source and source spectral width were used in measuring pulse spread. If the operating center wavelength changes, that too will affect the expected pulse spread.

The reader should consult the appendices if calculations based on this chapter yield borderline values. More information is then required to guarantee an acceptable margin of performance. Additional information from the vendor may be called for.

(4) Determining the dispersion limit.

If a system is limited by dispersion, it will be manifested in terms of intersymbol interference, i.e., for the digital system. In the analog system, dispersion limits the overall bandwidth. For this discussion, we will limit our consideration to the digital design. Intersymbol interference is experienced when the received pulse extends beyond its specified time slot, T, adding interfering power into an adjacent time slot. Some overlap can be tolerated depending upon the specific system, signal conditioning that may follow the detector, and the allowed BER.

In order to determine the dispersion limits for the optical fiber we can take the maximum bit-rate as*

$$R_m = \frac{1}{2\Delta\tau \cdot L} . \tag{6-20}$$

If the dispersion term is given in ns/km for the fiber in question, the total pulse spread will be $(\Delta\tau)L$, where L is the fiber length. This can, in general, be restricted to one-half the time slot T (other criteria can be used for specific systems, signal formats, or lower BER) for a BER of 10^{-9}. Thus,

$$(\Delta\tau) L \lessapprox \frac{T}{2} = \frac{1}{2R} , \tag{6-21}$$

where R is the data rate, and the last equality follows from Equation (6-20). Using this criterion, it is possible to specify a "figure of merit" for the fiber as the R·L product, which, from Equation (6-21), is

$$R \cdot L = \frac{1}{2\Delta\tau} . \tag{6-22}$$

From this expression, we see that the specified dispersion parameter immediately provides the length-bit-rate product, and an insight to the tradeoff possibilities for a specific fiber. For example, assume a fiber with a given value of $\Delta\tau$ = 20 ns/km. Then the R·L product is 50 Mb/s·km, which means we could use this fiber in a 5 Mb/s system with a total length of 10 km, or a 25 Mb/s system over a fiber length of 2 km, etc., provided, of course, that the system is not power limited.

Equation (6-22) is also used to determine if a particular design (already evaluated for the power-limited regime) is near the dispersion limit. In this case, the required bit-rate, R, has been specified and the length of the fiber permissible for the power limit has been determined in accord with the upper part of [illegible]e flow diagram of Table 6-1. The next step is to follow the

[illegible]tually, the denominator of this equation should be total pulse width at the detector and that width depends on input pulse width and response time of the detector. We assume here that fiber dispersion is the dominant term.

lower half of this diagram, which is simplified in this example since we are assuming that the specified value of $\Delta\tau$ includes all of the listed dispersion factors. We solve Equation (6-22) for L as

$$L = \frac{1}{2(\Delta\tau)R} \cdot \qquad (6\text{-}23)$$

Evaluation of this expression for $\Delta\tau$ and R used in the power-limited design yields the permissible length (between repeaters, or end-to-end) for the dispersion-limited mode. If the length L, in the latter case, is longer than that determined for the power-limited case, then the system is truly power limited.

Examples of both the general design procedure outlined above, and a more detailed design requiring special attention to operating parameters are given in Appendices B and C, respectively.

6-4. CONCLUDING REMARKS

In this chapter, we outlined and discussed the various factors which impact on component selection and tradeoffs. In Tables 6-1 and 6-2, we illustrated the technique. Table 6-1, in particular, gives the plan (discussed in this chapter) by which a user can analyze the performance of a proposed system or design a system of his own. The iterative technique involves a comparison between the power limited and the dispersion limited regime of operation. The dispersion limited regime is much more tolerant of degradation than is the power limited regime. A user must be able to adjust distance between terminals to guarantee communication as intended. This calls for a comparison as suggested in Table 6-1.

In the preceding sections of this chapter, we have discussed each of the terms that contribute to system losses so that distance between terminals for power-limited operation can be determined. We also discussed each of the contributors to dispersion so that the maximum distance between terminals in the dispersion-limited regime can be determined. A comparison of these results will then allow the designer to determine which

components are limiting throughput. He may then have to consider changes in components and/or parameters until the design meets the performance criteria.

In Appendix A details are given that are relevant to some of the more involved concepts discussed in this chapter. The results of this chapter and of Appendix A are then used in Appendix B, which is concerned with the design of a long-haul, high bit-rate system. Most of the attention in Appendix B is directed to the selection of the fiber. This is by far the most crucial task for this type of system since there are two competing candidates having important tradeoff possibilities. Those tradeoffs must be considered carefully in order to specify an economically viable system. Appendix C presents a design example for a relatively short link, but related to some specific communication system parameters.

REFERENCES

Bergh, A.A., and P.J. Dean (1972), Light emitting diodes, Proc. IEEE 60, No. 2, pp. 156-223.

Biard, J.R., and L.L. Stewart (1974), Optoelectronic data transmission, IEEE Electromagnetic Compatability Symposium Record, San Francisco, CA, July.

Biard, J.R., and L.L. Stewart (1973), Optoelectronic data bus, Final Technical Report AFAL-TR-271.

Borner, M. (1975), Status of fiber transmission research in Germany, Topical Meeting on Optical Fiber Transmission, Williamsburg, VA, January.

Burrus, C.A., and B.I. Miller (1971), Small-area double heterostructure aluminum-gallium arsenide electroluminescent diode sources for optical-fiber transmission lines, Opt. Comm., 4, pp. 307-309.

Casper, P.W. (1975), Optoelectronics and interface electronics, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 63, pp. 19-27, August.

Crow, J.D., J.S. Harper, L.D. Comerford, M.J. Brady, and R.A. Laff (1977), GaAs laser source package for multichannel optical links, Topical Meeting on Optical Fiber Transmission II, Digest, Williamsburg, VA, February.

Dierschke, E.G. (1975), Surface emitting sources for optical waveguides, Proceedings of the Society of Photo-optical Instrumentation Engineers, Vol. 63, pp. 90-98, August.

Dworak, R.G. (1977), private communication (GTE).

Dyott, R.R., J.R. Stern, and J.S. Stewart (1972), Fusion junctions for glass-fiber waveguides, Electronic Letters, 8, pp. 290-291.

EG&G (1977), Silicon photodiode application notes, Application Note D3000C-2, EG&G Inc., Electro-Optics Division, Salem, MA, January.

Electromechanical Design (1971), Miller-coded recorders pack 10 time more information, Digital Desing Section, Electromechanical Design, March.

Eppes, T.A., J.E. Goell, and C. Kao (1976), Use of optical fibers for long-range data communications, Electronic Design, 8, April.

Evtuhov, V., and A. Yariv (1975), GaAs and GaAlAs devices for integrated optics, IEEE Trans. MTT-23, pp. 44-57.

Fleming, J.W. (1976), Material and mode dispersion in $GeO_2 \cdot B_2O_3 \cdot SiO_2$ glasses, Journal of the American Ceramic Society, Vol. 59, November-December.

Fujita, H., Y. Suzaki, and A. Tachibana (1976), Optical fiber splicing technique with a CO_2 laser, Appl. Optics, 15, pp. 320-321.

GCC (1977), Optical-fiber cable type AT, General Cable Corporation Issue AT-4, July.

Gallawa, R.L. (1976), A user's manual for optical waveguide communications, OT Report 76-83, Office of Telecommunications, U.S. Department of Commerce, March. (NTIS Access No. PB 252901).

Gallawa, R.L. (1974), Design curves for optical waveguide digital communications, Tech. Report No. ACC-ACD-12-74, U. S. Army Communications Command, Fort Huachuca, AZ, December.

Goell, J.E. (1974), An optical repeater with high-impedance input amplifier, BSTJ, Vol. 53, No. 4, pp. 629-643.

Goell, J.E., T.A. Eppes and C. Kao (1975), Long distance repeatered fiber optical communications systems, Proc. of the Soc. of Photo-optical Instru. Eng., Vol. 63, pp. 50-57, August.

Hoss, R., and F. Weigl (1975), A fiber optically linked 100 channel voice intercom, Topical Meeting on Optical Fiber Transmission, Williamsburg, VA, January.

ITT (1977), Optical fiber communications link design, Tech. Note R-1, ITT Electro-Optical Products Div., Roanoke, VA.

Jaeger, R.E. (1976), Optical communication fiber fabrication, Electro Optics/Laser 76 Conference, New York, NY, September.

Kapron, F.P., and D.B. Keck (1971), Pulse transmission through a dielectric optical waveguide, Appl. Opt., 10, pp. 1519-1523.

Kawamoto, H., and D.J. Miller, III (1975), Nanosecond pulsing of GaAlAs lasers with carrier injection triggered trapatt device, Topical Meeting on Optical Fiber Transmission, Williamsburg, VA, January.

Kawamoto, H. (1973), Trapped-plasma triggered by carrier injection, Applied Physics Letters, Vol. 23, No. 5, pp. 251-272.

King, F.D., and A.J. Springthrope (1975), The integral lens coupled LED, J. Elec. Mat. 4, pp. 243-253.

Kressel, H. (1977), Laser diodes for fiber communications, Topical Meeting on Optical Fiber Transmission II, Digest, Williamsburg, VA, February 22-24.

Kressel, H., I. Tadany, M. Ettenberg, and H.F. Lockwood (1976), Light sources, Physics Today, May, pp. 38-47.

Kunze, D., H.J. Krimmling, H. Liertz and E. Bachel (1976), Jointing techniques for optical cables, Paper VIII-4, Proc. of 2nd European Conf. on Optical Fiber Communications, Paris, pp. 257-260.

A.D. Little, Inc. (1976), Electro-optic communications, Phase II, Report No. C-78866, Office of Telecommunications Contract No. 6-35600, November.

Machol, Robert E. (Ed.)(1965), System Engineering Handbook, (McGraw-Hill Book Company, New York, New York).

Makuch, J. (1977), private communication. (Amphenol)

Malitson, I.H. (1965), Interspecimen comparison of the refractive index of fused silica, J. Opt. Soc. of Am., 55, No. 10, pp. 1205-1209.

McDevitt, F. Ray (1975), System design methodology for guided optical communication links, Proc. of the Society of Photo-optical Instrumentation Engineers, Vol. 63, August, pp. 31-41.

Miller, C.M. (1975), Loose tube splices for optical fibers, Bell System Tech. J., 54, pp. 1215-1225.

O'Brien, J.T. (1976), Sources; laser diodes provide high power for high-speed communications systems, Electronics, Vol. 49, No. 16, August.

Ozeki, T., and E.H. Hara (1976), Measurement of nonlinear distortion in light emitting diodes, Electronic Letters, Vol. 12, No. 3.

Pan, J.J. (1975), High-frequency, wideband fiber-optic link, Topical Meeting on Optical Fiber Transmission, Williamsburg, VA, January.

Payne, D.N., W.A. Gambling, and B. Luther-Davies (1975), Measurement of the properties of low-loss phosphosilicate core fibers, Topical Meeting in Optical Fiber Transmission, Williamsburg, VA, January.

Personick, S.D. (1973), Receiver design for digital fiber optic communication systems, I and II, BSTJ, Vol. 52, No. 6, pp. 843-886, July-August.

Rawson, E.G., and R.E. Norton (1975), A halfkilometer, 150 M bit/sec data link experiment, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol 63, pp. 99-103, August.

Ross, M. (1975), Source modulation, Lecture Notes on Optical Communication, University of Colorado, Boulder, Colorado, August.

Schiel, E. (1975), Light emitting diodes and injection lasers for fiber optic communication systems, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 63, pp. 83-89, August.

Straus, J., and O.I. Szentesi (1977), Linearized transmitters for optical communications, 1977 IEEE International Symposium on Circuits and Systems, Phoenix, AZ, April 25-27.

Television Digest (1977), Lasers with 1-million-hour life, (news release), Vol. 17, No. 27, July.

Wendland, P.H., R.M. Madden and B. Kelly (1976), Detectors: inexpensive p-i-n photodiodes match fiber, source characteristics, Electronics, Vol. 49, No. 16, August.

Wittke, J.P. (1975), Optical fiber communications link design, Proceedings of the Society of Photo-Optical Instrumentation Engineers, Vol. 63, pp. 58-67, August.

APPENDIX A
FIBERS FOR LONG-HAUL, HIGH BIT-RATE SYSTEMS

A-1. INTRODUCTION

The selection of components for high bit-rate, long-haul systems is difficult because the tradeoffs are, in many cases, difficult to evaluate. Both the economics and the reliability of the system are profoundly affected by repeater spacing.

There are two competing views on the selection of the fiber and other components. One view holds that the graded-index fiber is the best choice because of bandwidth and ease of coupling; the alternative is the single-mode waveguide with its improved range-bit-rate product but difficult coupling and splicing. Technological developments in the past three years has shed new light on these alternatives and the advantages of each. It appears that some of the problems associated with single-mode transmission are being resolved, rendering that medium quite attractive. Theoretical and experimental work on the graded-index fiber has yielded new insight to that medium as well, and operation at the optimum wavelength is now better understood, yielding encouraging predictions.

A key factor in the selection of fiber type is the development of terminal components which operate at wavelengths of 1.1 μm or longer. Interest in such components stems from the fact that waveguide characteristics are substantially improved in a window which extends from about 1.2 μm to 1.4 um. depending on the precise composition of the fiber material. In that window, there occurs a fortuitous combination of low attenuation (less than 0.5 dB/km has been reported) and low total dispersion. Attention has turned more vigorously to this wavelength range in the past three years, with the result that significant improvements have now been realized.

The construction of laser diodes for the longer wavelengths involves a materials problem already encountered in connection with AlGaAs laser diodes (0.85-0.9 μm), which now have expected lifetimes of 10^6 hours (Hartman, et al., 1977) at room temperature.

Various material compounds (including binary, ternary, and quaternary) are being examined for close lattice parameter match at the heterojunctions to minimize interfacial recombinations. Among other requirements, it is crucial that threshold current densities of less than about 3000 A/cm^2 be achieved. The most promising candidate for the active system is InGaAsP. The first life test of such lasers yielded excellent results, and indications are that GaInAsP/InP laser diodes may not be subject to the same degradation mechanisms as GaAlAs laser diodes (Shen, et al., 1977). It appears now that laser diodes capable of acceptable operational properties at the longer wavelengths are within reach. Continuous cw operation of double-heterostructure laser diodes in the stripe geometry format has already exceeded several tens of thousands of hours. With the experience gained in earlier work at 0.85 μm, which led to projected lifetimes of 10^6 hours, there is reason to be optimistic about operation at the longer wavelengths, where the fiber has extraordinary properties.

In order to maximize the information-carrying capacity of multimode fibers (which enjoy several key advantages over the single-mode counterpart), the refractive index must change slowly and in accordance with specified laws. In the past three years, workers have gained a new understanding of the optimum index profile. The refinements now available are based on theoretical and experimental work reported in 1976. In particular, Olshansky and Keck (1976) showed that factors that had previously been ignored in optimizing the refractive index profile can have a significant and profound effect on the optimum value of the so-called α parameter. The profiles of interest belong to the family defined by (A-1):

$$
\begin{aligned}
n(r) &= n_1\sqrt{1-2\Delta(r/a)^{\alpha}} \qquad r \le a \; , \\
n(r) &= n_1\sqrt{1-2\Delta} = n_2 \qquad r \ge a \; .
\end{aligned}
\tag{A-1}
$$

It is now clear that the dispersive nature of the core and cladding glasses must be considered separately as functions of λ;

i.e., $\Delta = \Delta(\lambda)$, and terms involving the derivative Δ' with respect to λ must be included in the prediction of pulse spreading. The predicted optimum value of α for operation at 0.9 μm changes from slightly less than 2 $(2[1-1.2\Delta])$ when Δ' is ignored to about 2.25 when it is accounted for, when the core material is TiO_2 doped fused silica and the cladding $(r>a)$ is pure fused silica. The theoretical predictions are substantiated by experimental measurements. In general, a shift of 10 to 20% (depending on glass composition) in the optimum value of α is predicted when the dispersive properties of core and cladding are more properly accounted for.

Closely related to this new understanding of optimum profile are new analytic studies of material and mode dispersion in various composition glasses that will be useful in optical waveguides. In particular, the work by Fleming (1976) gave important new data on refractive index properties of bulk glass specimens belonging to the germanium borosilicate family. The reported work constituted an important supplement to previous data on silica, which was published nearly thirteen years ago (Malitson, 1965). The work by Fleming concentrated on nine samples of glass compositions ranging from 100% (mol %) SiO_2 to 86.5% 13.5% B_2O_3. Germanium doping was also included, The result is a useful display of values of n, n'', Δ, Δ', and optimum values of α for several important glass samples (Malitson, 1965; Fleming, 1976).

It has long been known that the single-mode waveguide has more confortable manufacturing tolerances and greater communication capability than the graded index fiber, but there has been a reluctance to invest heavily in active research because of two factors: (1) knowledge that only the laser diode (to the exclusion of the LED) could couple reasonable amounts of energy into the single mode fiber, and the associated questionable reliability of the laser diode; and (2) the anticipated splicing and coupling problems are known to be significant because of the small size of the fiber core. Remarkable progress has been reported in the past three years on these two problem areas and this has resulted

in renewed interest in the single-mode waveguide. The rejuvenation has been accentuated by reports that the loss of laboratory monomode fibers is now less than 0.5 dB/km. This is an important development since it is generally conceded that the attenuation of monomode fibers is expected to be higher than that of multimode fibers. In addition, monomode fibers are amenable to more precise analysis, leading to a more accurate prediction of optimum wavelength.

The use of lenses at the input to single-mode fibers has enhanced coupling capabilities. It now seems certain that an adequate amount of power can be coupled into the fiber, virtually assuring a range-bandwidth product of more than 10^{10} (bits/s)·km. Anticipated operation at $\lambda = 1.3$ μm is even more optimistic because of reduced dispersion and reduced attenuation at that longer wavelength.

Efficient splicing of monomode fibers has been accomplished using a fusion technique (Bisbee, 1976; Tsuchiya & Hatakeyama, 1977). The technique relies on the self-alignment owing to surface tension of melted fiber ends. The technique is quite promising, and has led to average splicing loss of 0.2 dB in fibers having core radii of only 7 μm. The technique seems suited to use in the field and has added an important new dimension to the ultimate use of single-mode fibers in future telecommunication systems.

A-2. CAPABILITIES OF SINGLE-MODE FIBERS

The analysis of single-mode fibers is fairly simple, now that the theory has produced approximations to the appropriate eigenvalue. This, coupled with a knowledge of $n(\lambda)$ for core and cladding allows determination of the range-bandwidth product. Both material and waveguide effects must be accounted for (see equation (A-2) below). To predict dispersion, one must know the normalized propagation constant b, as a function of λ, for the HE_{11} mode of the waveguide (b is defined below). Several approximations to b are available, each valid only over a limited range of the normalized frequency V. Actually, only values of V close to

2.405* are of interest since prudence demands that operation be close to multimode to reduce radiation and coupling problems. Since practical waveguides are not step index (for obvious physical reasons), operation can usually be at V slightly greater than 2.405, depending on the value of α appropriate to the actual single-mode guide. A reasonable approximation is

$$V = 2.405 \sqrt{\frac{\alpha+2}{\alpha}} ,$$

for single-mode operation.

An accurate and useful approximation to the value of b (Rudolph and Neumann, 1976) is:

$$b = w^2/V^2 ,$$

where

$$w = 1.1428V - 0.9960$$

for $1.5 \leq V \leq 2.8$. This straight-line representation of w as a function of V is found to yield surprisingly accurate results for the range of interest.

An effective refractive index of single-mode fibers can be defined such that all sources of intramodal dispersion are accounted for:

$$n = n_1 \; [1-\Delta(1-b)] = \beta/k \qquad \text{(A-2)}$$

where

β = axial wavenumber.

k = free-space wavenumber.

n_1 = refractive index of the core material.

$\Delta = (n_1^2-n_2^2)/2n_1^2$; measure of contrast.

n_2 = refractive index of the clad material.

b = normalized propagation constant, known only approximately in most cases of practical interest.

*This number comes from mode theory using Maxwell's equations; the zero order Bessel function is zero when the argument equals 2.405.

All of the terms in Equation (A-2) are functions of wavelength and it is this fact that leads to pulse dispersion. Identification of dispersion terms is as follows:

Material Dispersion: variation of n_1 with λ

Profile Dispersion: variation of Δ with λ

Waveguide Dispersion: variation of b with λ.

From this expression for n, we can identify the group index, N, as follows:

$$N = \frac{d(\nu n)}{d\nu} = n - \lambda \frac{dn}{d\lambda} , \tag{A-3}$$

where ν is frequency. From this, a Taylor series can be used to determine pulse spread per unit length due to finite source spectral width, $(\Delta\lambda)$:

$$\tau = \frac{1}{c} \left[(\Delta\lambda) D_1 + \frac{(\Delta\lambda)^2}{2!} D_2 + \frac{(\Delta\lambda)^3}{3!} D_3 + \ldots \right], \tag{A-4}$$

where

$$D_n = \frac{d}{d\lambda} D_{n-1}$$

$$D_1 = \frac{dN}{d\lambda} = -\lambda \frac{d^2n}{d\lambda^2} .$$

As the operating wavelength changes, the relative magnitude of each term in Equation (A-4) changes. One of the key advantages of single-mode operation is being able (at least theoretically) to operate at a wavelength where D_1 vanishes or where the sum of the first two terms (involving D_1 and D_2) vanishes. Since $(\Delta\lambda)$ is small for good quality laser diodes, it is desirable to select the operating wavelength such that at least D_1 vanishes. In that case, pulse spread is proportional to $(\Delta\lambda)^2$. Values of D_n are difficult to obtain since they depend on the glass and the dopant materials as well as dopant concentration.

Knowing how N varies with λ allows evaluation of D_n. This, in turn, reveals important information on the optimum value of λ. Figure A-1 shows n, n_1, N, and N_1 as functions of λ; the subscript 1 refers to the core and the unsubscripted terms

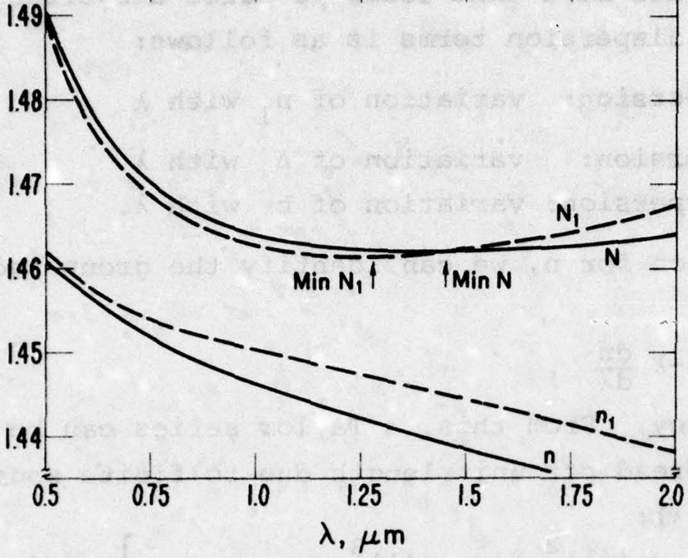


Figure A-1. Refractive index and group index for silica.

include both material and waveguide effects. The curves of Figure A-1 are for pure silica core with constant Δ (=0.006). Note that silica material dispersion, characterized by N_1, goes through a minimum at $\lambda = 1.27$ µm. This has been reported frequently in the literature and is the source of enthusiasm for operating at this wavelength. At $\lambda = 1.27$ µm, $dN_1/d\lambda = 0$. However, of more significance is the fact that at a slightly longer wavelength (1.45 µm), the group index N passes through a minimum. This is a more desirable wavelength than 1.27 µm, which can be seen by examining (A-4) which is repeated below. For $\lambda = 1.45$ µm, $dN/d\lambda = 0$, and the pulse width is proportional to the second power of source spectral width, $\Delta\lambda$ (neglecting higher-order terms)

$$\tau = \frac{1}{c}\left[(\Delta\lambda)\frac{dN}{d\lambda} + \frac{(\Delta\lambda)^2}{2!}\frac{d^2N}{d\lambda^2} + \frac{(\Delta\lambda)^3}{3!}\frac{d^3N}{d\lambda^3} + \ . \ . \ . \ \right] .$$

A-3. MULTIMODE FIBERS

In this section, we will restrict attention to the multimode graded-index fiber, for which the refractive index profile satisfies Equation (A-1), repeated for convenience:

$$n(r) = n_1\left(1-2\Delta\left(\frac{r}{a}\right)^{\alpha}\right)^{1/2} \qquad r \leq a$$

$$n(r) = n_1(1-2\Delta)^{1/2} \qquad r \geq a$$

where n_1, n_2, and Δ were defined earlier, and a is, as usual, the core radius; α is the so-called profile parameter. In the special case of large α, the step index fiber is encountered. Thus, we can concentrate on this family of profiles as being quite general.

In such multimode fibers, the pulse broadening is composed of an intermodal contribution and an intramodal term. The rms pulse width is then the square root of the sum of the squares of the two contributions.

When the profile dispersion term is included, the optimum value of α is given by (Olshansky and Keck, 1972)

$$\alpha_{opt} = 2 + p - \Delta\,\frac{(4+p)(3+p)}{(5+2p)}, \qquad \text{(A-5)}$$

where p is the profile dispersion term, given by

$$p = \frac{-2n_1\lambda}{N_1\Delta}\,\frac{d\Delta}{d\lambda}, \qquad \text{(A-6)}$$

and the subscript 1 refers to the core region. Note that if $p = 0$, $\alpha_{opt} = 2-2.4\Delta$, a value slightly less than 2 since Δ is small and positive. When p is not neglected, the optimum value of α may be greater than 2.

The rms width due to intermodal broadening (subscript e) is given by

$$\tau_e = \frac{LN_1\Delta}{2c}\,\frac{\alpha}{\alpha+1}\left[\frac{\alpha+2}{3\alpha+2}\right]^{1/2}\left[C_1^2 + \frac{4C_1C_2\Delta(\alpha+1)}{2\alpha+1} + \frac{4\Delta^2C_2^2(2\alpha+2)^2}{(5\alpha+2)(3\alpha+2)}\right]^{1/2} \qquad \text{(A-7)}$$

where

$$C_1 = \frac{\alpha-2-p}{\alpha+2},$$

$$C_2 = \frac{3\alpha-2-2p}{2(\alpha+2)}.$$

The intramodal term (subscript a) is

$$\tau_a = \frac{(\Delta\lambda)}{\lambda}\left[\left(\frac{dN_1}{d\lambda}\right)^2 + 2\,\frac{dN_1}{d\lambda}\,(N_1\Delta)\left(\frac{\alpha-2-p}{\alpha+2}\right)\left(\frac{2\alpha}{2\alpha+2}\right) + (N_1\Delta)^2\left(\frac{\alpha-2-p}{\alpha+2}\right)^2 \frac{2\alpha}{3\alpha+2}\right]^{1/2} \qquad \text{(A-8)}$$

where $(\Delta\lambda)$ is the rms source spectral width.

It is instructive to consider certain limiting values of Equation (A-7). When p is ignored and $\alpha = \alpha_{opt}$,

$$\tau_e = \frac{LN_1\Delta^2}{c\ 20\sqrt{3}}\ . \qquad \text{(A-9)}$$

For the step index fiber, the value of p is inconsequential and

$$\tau_e = \frac{LN_1\Delta}{c\ 2\sqrt{3}}\ . \qquad \text{(A-10)}$$

Thus, the graded index fiber has the potential of reducing pulse spread by a factor of about 1000 compared to step index fibers, for typical values of $\Delta(\cong 0.01)$.

REFERENCES
APPENDIX A

Bisbee, D.L. (1976), Splicing silica fibers with an electric arc, Appl. Opt., Vol. 15, pp. 796-798.

Fleming, J.W. (1976), Material and mode dispersion in $G_eO_2 \cdot B_2O_3 \cdot SiO_2$ glasses, J. Am. Ceramic Soc., Vol. 59, pp. 503-507.

Hartman, R.L., N.E. Schumaker, and R.W. Dixon (1977), Continuously operated (AlGa)As double heterostructure lasers with 70°C lifetimes as long as two years, Appl. Phys. Lett., Vol. 31, pp. 756-759.

Malitson, I.H. (1965), Interspecimen comparison of the refractive index of fused silica, J. Opt. Soc. Am., Vol. 55, pp. 1205-1209.

Olshansky, R., and D.B. Keck (1976), Pulse broadening in graded-index optical fibers, Appl. Opt., Vol. 15, pp. 483-491.

Rudolph, Hans-Dieter and E.G. Neumann (1976), Approximations for the eigenvalues of the fundamental mode of a step index glass fiber waveguide, Nachrichtentechn, Vol. 29, pp. 328-329.

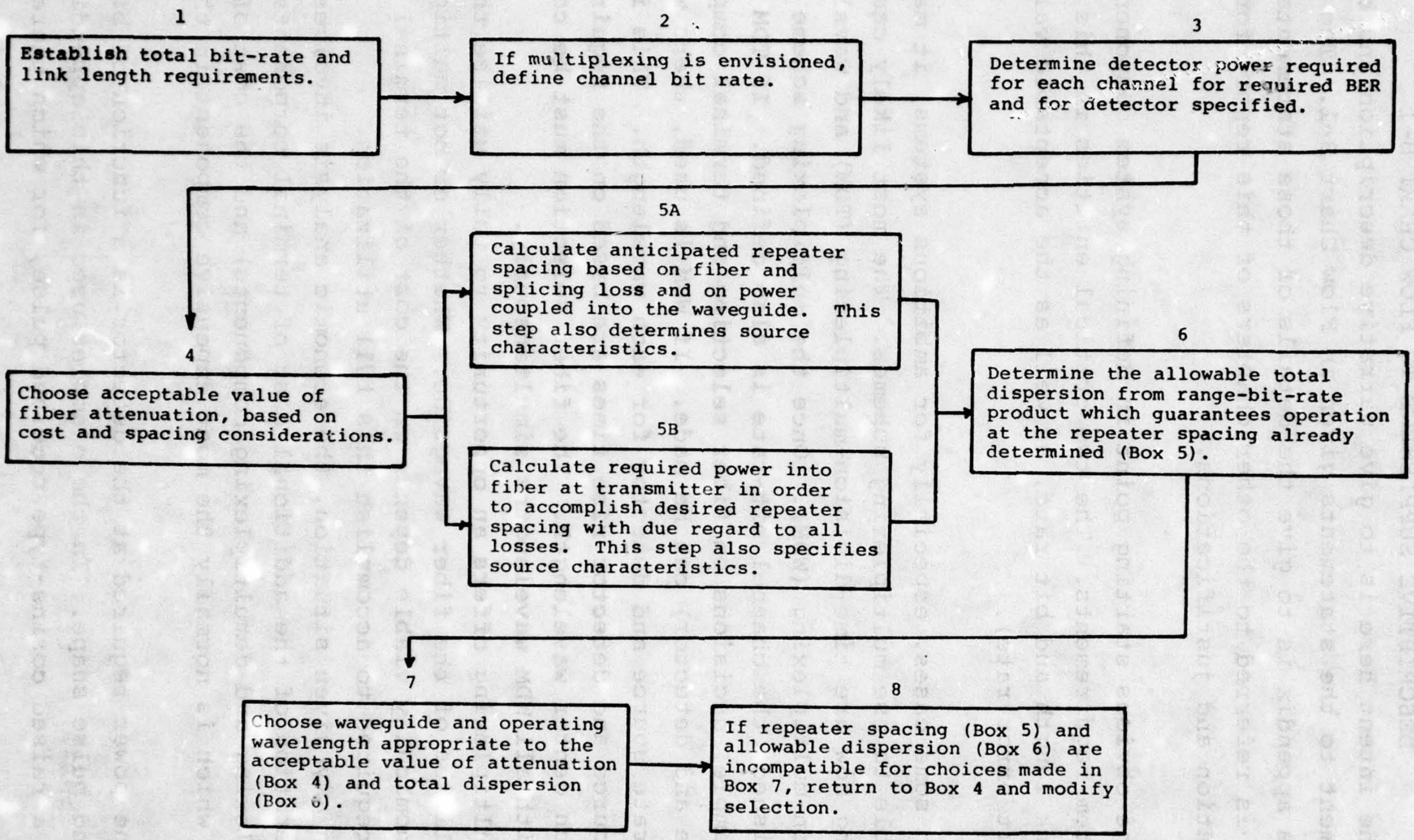
Shen, C.C., J.J. Hsieh, and T.A. Lind (1977), 1000-hour continuous cw operation of double-heterostructure GaInAsP/InP lasers, Paper WB4, Digest of technical papers presented at the Topical Meeting on Optical Fibers Transmission II, Williamsburg, VA, February.

Tsuchiya, H., and I. Hatakeyama (1977), Fusion splices for single-mode optical fibers, Paper PD1 (Post-Deadline), Digest of technical papers presented at the Topical Meeting on Optical Fiber Transmission II, Williamsburg, VA, February.

APPENDIX B
METHODOLOGY FOR COMPONENT SELECTION FOR LONG-HAUL, HIGH BIT-RATE SYSTEMS

To illustrate the concepts discussed in Chapter 6, we consider here the problem of selecting components for a long-haul, high bit-rate system. This is an intriguing challenge in view of important recent developments which appear to bode feasibility for well-designed optical waveguide systems. A flow chart of the methodology is given on the following page; it is followed by a brief descriptive supplement on the following two pages.

FLOW CHART B-1*



*Descriptive supplement to this Flow Chart is given on the next two pages.

DESCRIPTIVE SUPPLEMENT TO FLOW CHART B-1

The intent here is to give narrative description and brief supplement to the statements given in Flow Chart B-1. The thrust of this appendix is to give the details of those statements. The reader is referred to the other chapters of this report for elaboration and justifications.

Step 1

The obvious starting point in defining system components is in system requirements. The two critical entities in this regard are link length and bit rate, as well as the acceptable value of BER (bit error rate).

Step 2

In some cases, especially for ambitious systems, it may be desirable to use multiplexing schemes. The most likely candidates emerging now are time-division-multiplexing (TDM) and wavelength-division-multiplexing (WDM). Once the multiplexing scheme is established, the channel bit-rate is also defined. If TDM is used, for example, decisions on fiber selection and terminal components (source and detector) can be made. If WDM is used, there will be a separate source and detector for each wavelength. This implies that source and detector rise times are based on the requirements for each center wavelength. The fiber selection must be compatible with all WDM wavelengths simultaneously.

Multiplexing offers an opportunity to fully utilize the capabilities of the fiber waveguide. Whether or not multiplexing is economically viable depends on the cost of the terminal components required to accomplish this full utilization.

In any given situation, the economic analysis involves a consideration of the additional cost of terminal components (i.e., multiplexing and demultiplexing components) and the cost of the fiber, which is normally the most expensive component in the system.

Step 3

The power required at the detector is a function of bit rate, BER, and pulse shape. In the examples used in this appendix, we assume a raised cosine-type received pulse, for which there is

now a fairly complete analytic basis. The power required will also depend on the detector and whether or not avalanche gain is used.

Step 4

Knowing the power required at the detector allows the specification of power loss budget and, thus, acceptable fiber attenuation. Actually, Steps 4 and 5 are intimately interrelated since attenuation, repeater spacing, and power coupled into the fiber are all interrelated. Specifying fiber attenuation will also depend on cost constraints, since the very low-loss fibers are expensive. Fiber loss should also allow for degradation and splicing losses.

Step 5A or 5B

The next step in the analysis determines repeater spacing based on source and coupling characteristics, or it determines the required power coupled into the fiber for assumed repeater spacing. In any case, the purpose of Step 5 is to insure that adequate power gets to the detector (cf. Step 3).

Step 6

The methodology now turns from power-limited operation to band-limited operation. The purpose of Step 6 is to determine if pulse dispersion characteristics are, in fact, limiting repeater spacing to a value less than that found in Step 5.

Step 7

Limits have now been placed on the waveguide to be used and, hence, the waveguide can now be specified. Since waveguide characteristics change with wavelenth, the selection made here also fixes wavelength.

Step 8

This step calls attention to the fact that component selection is an iterative process. If an incompatibility is found in the process, then parameters must be changed and the process reworked. To illustrate, we note that choosing an avalanche detector may remove an incompatibility arising from the planned use of direct detection.

B-1. POWER REQUIRED AT THE DETECTOR

For systems requiring a large range-bandwidth product, it is clear that one must select components carefully in order that the repeater spacing be maximized. The advantage of using an APD rather than direct detection can be seen from Figure 6-1(b). For a data rate of 100 Mb/s, for example, the advantage is about 15 dB and the advantage increases comfortably with the data rate. This 15 dB advantage translates into repeater spacing of 15 km if the attenuation is 1 dB/km, assuming that optical power at the detector is the limiting factor. The 1 dB/km allowance for fiber attenuation is an acceptable allowance for sophisticated systems envisioned for the near future. Laboratory fibers having attenuation of less than 0.5 dB/km at 1.2 μm are now being reported routinely, and in one case workers reported drawing a fiber 14 km long having attenuation of 0.5 dB/km at 1.3 μm and at 1.5 μm (Niizeki, 1978). Attenuation was 2 dB/km at 0.85 μm. Thus, even allowing for splices (which normally have loss less than 0.5 dB) and cabling loss, the 1 dB/km allowance is reasonable. In the data used later, we will use 1 dB/km at $\lambda > 1 \mu m$ and 2 dB/km at $\lambda = 0.9$ μm.

For purposes of this discussion, we will assume a specific bit-rate requirement. Any other requirement can be considered using the methodology described here. We take the required bit rate as 500 Mb/s. Then using Equations (6-6) and (6-7)(cf. also fig. 6-1a), we find the following:

$$G_{opt} = 57 \left(\frac{500}{25}\right)^{1/3} = 155,$$

$$P_d = 1.64 \left(\frac{500}{25}\right)^{7/6} \text{ nW} = 54 \text{ nW} = -43 \text{ dBm}.$$

This required power at the detector is calculated following the discussion in Section 6-3. Note that the advantage of using optimum gain is

$$\frac{3.25 \times 10^{-8}}{1.64 \times 10^{-9}} \frac{\left(\frac{500}{25}\right)^{3/2}}{\left(\frac{500}{25}\right)^{7/6}} = 54.8 = 17 \text{ dB}.$$

In most cases, especially where, for purposes of maintenance and reliability, it is desirable to minimize the number of repeaters, this advantage fully justifies the additional cost and complexity of using avalanche gain.

We assume that power coupled into the waveguide is 1 mW (0 dBm). If a single-mode waveguide is selected (this will be discussed further below), the small size of the core makes it difficult to couple energy into the fiber efficiently unless a lens is used. Elliptic lenses can be designed to match the elliptic field of the typical stripe geometry laser diode to the circular geometry of the waveguide. In case a graded-index fiber is used, the core size is more comfortable but the graded refractive index reduces the mode volume of the fiber compared to the step-index fiber, so the power-gathering ability is hampered accordingly (cf. fig. 6-5). Nevertheless, it is reasonable to assume that, with some care, 1 mW of power can be coupled into the fiber. Thus, the allowed total attenuation between repeaters is 43 dB. This corresponds to a repeater spacing of 43 km at the long wavelengths ($\lambda > 1$ nm) and 21 km at 0.9 μm, using the attenuation guidelines assumed above.

B-2. REQUIRED RANGE-BANDWIDTH PRODUCT

If the repeaters are spaced 43 km (or 21 km) apart, the required range-bit-rate product is

$$43 \cdot 500 \text{ (Mb/s)} \cdot \text{km} = 21.5 \text{ (Gb/s)} \cdot \text{km}, \quad \text{or}$$
$$21 \cdot 500 \text{ (Mb/s)} \cdot \text{km} = 10.5 \text{ (Gb/s)} \cdot \text{km}.$$

If the pulse spread is excessive, this range-bandwidth product cannot be achieved and the system will be dispersion limited, requiring that the repeater spacing be reduced.

Using Equation (6-22), we note that $\Delta\tau$ must not exceed 2.3×10^{-11} s/km or 23 ps/km (47.6 ps/km at 0.9 μm). This rather stringent requirement is not easily met and fiber selection and wavelength specification must be done carefully. Not specifically considered here is the possibility of using wavelength division multiplexing (WDM) to accomplish the 500 Mb/s on, say, five

separate channels, each providing 100 Mb/s. Using WDM, one uses several (in this case, 5) laser diodes on a thin film integrated circuit chip, each operating at a different wavelength. The five laser diodes couple into branched waveguides that feed the three outputs onto a single waveguide. The most promising approach to such a technique involves the use of heterojunction diode lasers operating in the distributed-feedback mode. This allows shifts of only a few nanometers in the lasing wavelength. Distributed-feedback lasers have the additional advantage of very narrow spectral width. Since they are injection lasers, modulation can be direct, involving the same options available to other such lasers. Demultiplexing can likewise be done on a grating chip. A diffraction grating will demultiplex the signals and feed each to its own photodetector. These concepts are still in the experimental stage and so will not be considered further in the analysis of the problem at hand. If such a WDM system were available, however, it is clear that the requirements on pulse spread would be relaxed by a factor of five, from 23 ps/km to about 115 ps/km at the longer wavelengths for each fiber.

Whether or not the required 23 ps/km (or 47.6 ps/km) is actually accomplished will depend on the selection of components. A user can specify the fiber waveguide within his guidelines of economics, availability, commonality, and logistics. The fiber cable vendors are only just beginning to understand the intricate interrelations between glass components and pulse dispersion. The normal starting material for low-loss waveguides is silica (SiO_2). The refractive index contrast is accomplished by doping the silica, to provide a refractive index either greater than or less than that of the silica. For purposes of discussion, we will assume the doping is 7 mol % G_eO_2 (referred to below as sample C, composed of silica and germanium borosilicate). The terms appropriate to a Sellmeier-type equation describing the refractive index of these materials are given by Fleming (1976) for samples C and F and by Malitson (1965) for sample A, pure silica.

B-3. WAVELENGTH AND WAVEGUIDE DEFINITION

Having determined the maximum allowable value of pulse spread (23 or 47.6 ps/km), we now turn to the options which are compatible with that requirement. We assume explicitly that the source and detector are fast enough to accommodate this bit rate. Implicit in this procedure is the assumption that total waveguide attenuation (including splicing losses) is no more than 1 dB/km or 2 dB/km, as discussed above. This is quite realistic, even though it is generally conceded that single-mode waveguides tend to be more lossy than multimode fibers and so, in principle, it should be more difficult to achieve in the single-mode case. Single-mode fibers have been drawn in 14 km lengths with attenuation of less than 0.5 dB/km. Thus, in 43 km, one would need only about three splices, using this figure as a basis.

A key decision now involves the specification of the operating wavelength and the waveguide. In the latter category, the choice is limited: only the graded-index multimode fiber with optimum (or near optimum) value of α and the single-mode fiber are likely candidates. The multimode step index fiber is not suitable because of the unacceptable dispersion it is known to exhibit. The data required to select from the options available are given in Section 6-3b and Appendix A.

Table B-1 gives calculated values of pulse spread and length-bit-rate product for several fibers under several operating conditions. The Table should be used in conjunction with Figures B-1 to B-5, which are included to give the reader a feeling for the peripheral considerations, including tolerances for the various parameters. The figures and the Table indicate that operation at 0.9 μm produces acceptable values of pulse dispersion for $\Delta\lambda$=0.0003 μm. Operation at 1.27 μm and 1.2 μm produces much more desirable results, and the single mode waveguide is significantly better than the graded index fiber. Note that a good quality laser diode is called for, preferably a distributed feedback laser for which $\Delta\lambda$=0.0003 is typical.

Table B-1. Pulse Spread

Fiber Type*	Wavelength (μm)	Fiber Material	Profile Parameter (α)	Source Spectral Width, Δλ (μm)	Pulse Spread (ps/km)	Range-Bit-Rate Product (Gb/s)·km
SM	0.9	Silica Core Δ=0.004		0.003 0.0003	270 28	1.8 17.9
GI	0.9	Samples A & C	Optimum (α=1.96)	0.003 0.0003	360 36	1.39 13.9
GI	0.9	Samples A & F	Optimum (α=2.42)	0.003 0.0003	300 30	1.67 16.7
SM	1.27	Silica Core Δ=0.004		0.003 0.0003	<1 <<1	>500 >>500
GI	1.2	Samples A & F	Optimum (α=2.7)	0.003 0.0003	1.5 1.2	333.3 416.7

*SM = Single Mode, a = 5μm.
GI = Graded Index Multimode.

Sample A: 100% SiO_2

Sample C: 93% SiO_2; 7% GeO_2

Sample F: 86.27% SiO_2; 9.7% B_2O_3; 4.03% GeO_2

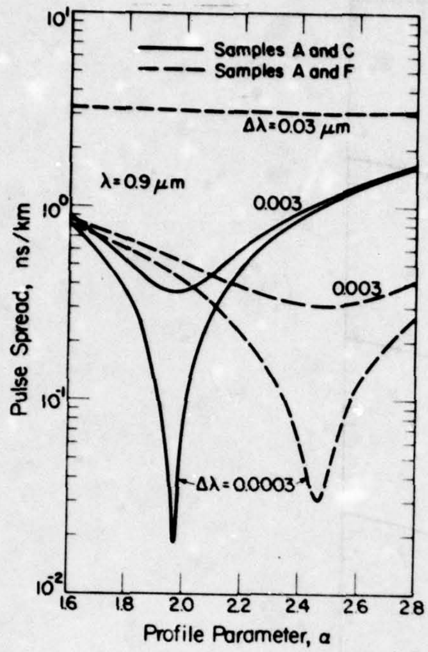


Figure B-1. Pulse spread vs profile parameter.

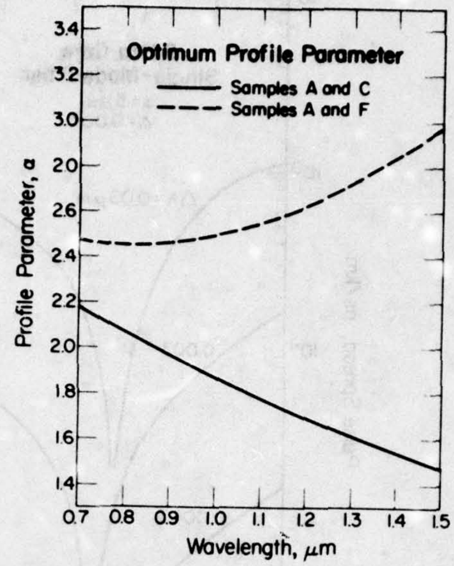


Figure B-2. Optimum profile parameter.

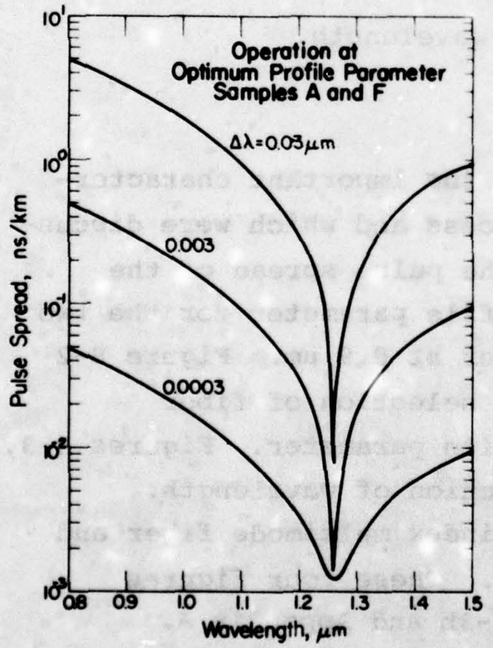


Figure B-3. Pulse spread vs wavelength.

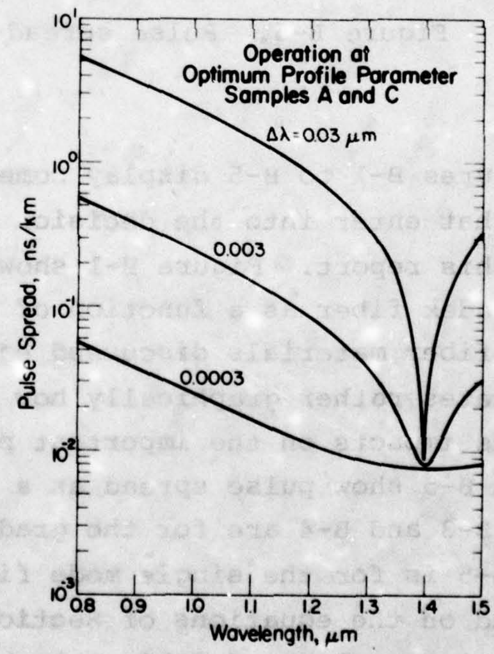


Figure B-4. Pulse spread vs wavelength.

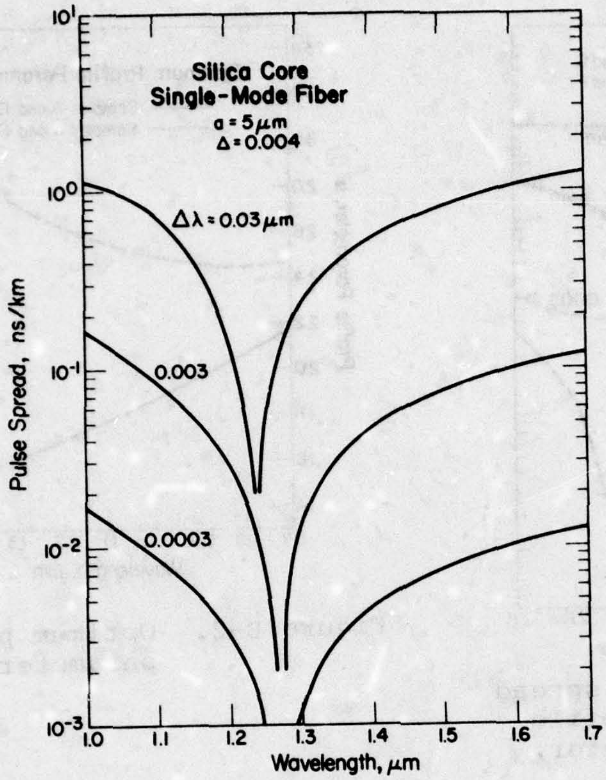


Figure B-5. Pulse spread vs wavelength.

Figures B-1 to B-5 display some of the important characteristics that enter into the decision process and which were discussed in this report. Figure B-1 shows the pulse spread of the graded index fiber as a function of profile parameter for the two typical fiber materials discussed earlier at 0.9 μm. Figure B-2 demonstrates rather graphically how the selection of fiber materials impacts on the important profile parameter. Figures B-3, B-4, and B-5 show pulse spread as a function of wavelength. Figures B-3 and B-4 are for the graded index multimode fiber and Figure B-5 is for the single mode fiber. These four figures are based on the equations of Section 6-3b and Appendix A.

The last column of Table B-1 shows that the single mode fiber is capable of about 17.9 (Gb/s)·km at 0.9 μm.

The curves are truncated in Figure B-5 because the analysis is not accurate near that critical wavelength, since only two terms were used in the Taylor series expansion of the appropriate equation.

B-4. SUMMARY OF SELECTED COMPONENTS

In this Appendix, we considered the selection of components for a 500 Mb/s long-haul system. We did not include multiplexing schemes although such schemes would result in increased repeater spacing but at increased cost of terminal components. Whether or not total system cost is reduced through the use of multiplexing schemes was not addressed.

The advantage of using avalanche gain for the system being considered amounts to 17 dB, which is rather substantial and would justify its inclusion. The optimum value of gain is 155, a value that could be obtained handily although biasing and stabilizing circuits would be required.

We discussed the use of a good quality laser diode having source spectral width of 0.0003 μm (0.3 nm). Since pulse spread depends critically on the source spectral width, that parameter plays a significant role in component selection. Distributed feedback lasers are typically capable of 0.3 nm widths.

The fiber waveguide selection for this example illustrates the emergence of pulse dispersion as a dominant factor when attenuation becomes suitably small. For a long-haul, high-bit-rate system such as the one considered here, a very low loss fiber is called for in order to minimize the number of repeaters required. Using 1 dB/km for the attenuation we found that a good quality graded index fiber (with optimum value of α (profile parameter)) or a single mode fiber would meet the needs.

The scope of this text does not allow inclusion of some of the subtle aspects of component selection. These more subtle aspects are often not within the province of the design engineer. As an illustration, we cite the "spot size" in a single mode waveguide. This is a measure of the field extent and depends more on refractive index contrast than on any other parameter. Thus, two

single mode guides, having identical values of normalized frequency, V, could have different values of contrast and hence different values of spot size. Thus, the two have different field operating characteristics by virtue of different coupling and splicing characteristics and different losses as a result of bends (micro and macro).

Another rather subtle point is encountered when a more detailed examination is made of the graded index fiber. It transpires that the tolerance on the profile parameter is very restrictive for many fiber materials. This is illustrated graphically in Figure B-1, by the solid curve (samples A and C) when $\Delta\lambda=0.0003$ μm. Note the dip in pulse spread is rather sharp, and thus even a slight deviation from the optimum value of α has a dramatic effect on the pulse spread. The broken curve shows a much more tolerant behavior. The reason for the differences can be seen by examining Figure B-2. These curves show that the optimum value of α is changing only slowly in the vicinity of 0.9 μm for samples A and F (broken curve), as opposed to a significant change (slope) in the same characteristic for samples A and C. In a given situation, the fiber available from the vendor cannot be too narrowly specified. Thus, to expect to buy a graded index fiber with the optimum profile may be expecting too much since the optimum profile depends on operating wavelength.

Another subtlety involves coupling power into the candidate fibers. Graded index fibers have reduced mode volume compared to step index fibers. Thus, input coupling efficiency is influenced by the value of α. For single mode fibers, on the other hand, the core size usually represents a severe restriction on input coupling efficiency. A lens can ease the problem considerably at the expense of tolerance on axial alignment.

REFERENCES
Appendix B

Fleming, J.W. (1976), Material and mode dispersion in $G_eO_2 \cdot B_2O_3 \cdot SiO_2$ glasses, J. Am. Ceramic Soc., Vol. 59, pp. 503-507.

Malitson, I.H. (1965), Interspecimen comparison of the refractive index of fused silica, U. Opt. Soc. of Am., 55, No. 10, pp. 1205-1209.

Niizeki, Nobukazu (1978), Single mode fiber at zero-dispersion wavelength, presented at the Topical Meeting on Integrated and Guided-Wave Optics, Salt Lake City, Utah, February.

APPENDIX C
A DESIGN EXAMPLE FOR A RELATIVELY SHORT FIBER OPTIC LINK
USING SPECIAL MODEM SPECIFICATIONS

C-1. INTRODUCTION AND STATEMENT OF THE PROBLEM

The objective of this appendix is to make use of the information and procedures given in this handbook, and thereby provide a design example for a relatively short fiber optic link. Appendices A and B have treated the special considerations and detail necessary for the long-haul link. This example begins with the premise that the design will be fairly straightforward. However, by inserting specific system parameters, we find the overall design leads to requirements similar to those considered in Appendix B.

The iterations required in the process are illustrated in the example, and we have emphasized some tradeoff options that the designer must or should consider, both conceptual and technical.

The example problem is to design a digital fiber-optic transmission system for use between a satellite communications ground station and a technical control center. The design is restricted to the consideration of a single fiber, with the connotation that the final design will embody a multi-fiber cable for use in meeting the requirements of some of the options considered. In addition, more fibers will need to be considered to provide for any duplex operation, or separate transmission of data and clock signals as may be required by the special modems introduced in Chapter 4. In other words, the design example is for a simplex system, where the results are applicable to either a data stream fiber or a clock fiber. Additional operational features (such as full duplex) will be accomplished with multi-fibers of the same type.

The assumed specifications and parameters for the desired link are as follows:

1. Length of link: 4 km.
2. Maximum transmission bit rate: 10 Mb/s.

3. Error performance (BER): < 1 in 10^6.
4. Communications system: Interconnect Facility (ICF) (see Section 4-4).

C-2. SYSTEM ARCHITECTURE AND IMPLEMENTATION

For this design example, we will assume the following for the architecture and implementation:

1. Any particular fiber that we select will be applicable in a ruggedized cable assembly.
2. The fiber cable will be supplied and capable of being pulled in lengths up to 1 km.
3. The installation of the cable will be made in either conduits, or suspended in appropriate fashion from overhead poles.
4. Field splices will be made where two cable sections meet, if a repeater is not required.
5. Cable connectors for disconnect purposes will be limited to end terminals and/or at repeater locations.
6. Duplex operation will be accomplished with multi-fiber cable, and special timing signals will use a separate fiber.

C-3. SYSTEM DESIGN

a. Power Limit Calculations

Following the process given by Table 6-1, we first compute the required power at the optical detector, using Equations (6-5) and (6-6). These expressions yield the required power under the conditions of no gain and optimum gain at the optical detector, respectively.

(1) Required power for no gain.

$$P_d = 3.25 \times 10^{-8} \left(\frac{R}{R_o}\right)^{3/2} \qquad \text{(C-1)}$$

$$= 3.25 \times 10^{-8} \left(\frac{10}{25}\right)^{3/2}$$

$$= 0.82 \times 10^{-8}\ \text{W} = 8.2\ \text{nW}$$

P_d(dB) = -51.0 dBm (no gain).

In this computation we recall that

R = operational bit rate

R_o = reference bit rate = 25 Mb/s.

(2) Required power for optimum gain.

$$P_d = 1.64 \times 10^{-9} \left(\frac{R}{R_o}\right)^{7/6} \tag{C-2}$$

$$= 1.64 \times 10^{-9} \left(\frac{10}{25}\right)^{7/6}$$

$$= 0.563 \times 10^{-9}\ \text{W} = 0.563\ \text{nW}$$

P_d(dB) = -62.5 dBm (optimum gain).

(3) Optimum gain (if required).

$$G_{opt} = G_r \left(\frac{R}{R_o}\right)^{1/3} \tag{C-3}$$

$$= 57 \left(\frac{10}{25}\right)^{1/3} = 42$$

G_{opt}(dB) = 10 log 42 = 16.2 dB.

(4) BER performance.

The expressions used in the above computations are valid for a BER of 1 in 10^9. It was noted in Chapter 6 that the BER performance is relatively insensitive to the received power level. Therefore, the computations above are conservative for the specified BER of 1 in 10^6. This will merely add a small increment to the design margin considered below.

(5) Detector coupling loss (L_c).

We note from the discussion in Chapter 6 that the total coupling loss for the system is due to the mismatch between the source and fiber, and between the fiber and detector. The loss at the source depends on a number of parameters as discussed in Chapter 6. In the design process however, this loss is accounted for in computing the power coupled into the fiber. This is dependent upon the source characteristics and the NA of the fiber, and is computed in (9) below. The loss encountered between the fiber and detector are generally much smaller, and can usually be estimated. The liberal rule noted in Section 6-3 is adopted here, giving

$L_c = 1$ dB (fiber/detector only).

(6) Splicing loss (L_s).

Splicing losses (based on cited data) are assumed to be about 0.5 dB per splice. In the architecture we have assumed, we would have a maximum of three splices giving a total loss of

$L_s = 3 \times 0.5 = 1.5$ dB.

(7) Fiber loss (L_f).

The fiber loss can only be calculated for a specific fiber. However, we can use the above results to determine an approximate value of the allowable fiber loss from Equation (6-7); which is repeated as

$$P_s(\text{dBm}) = P_d(\text{dBm}) + L_c + L_s + L_f + L_m .$$

At this point, we shall include, as a part of the margin term L_m, a 3 dB loss as a derating value for the source. Thus, the power required of the source for the no gain and optimum gain cases is given by

$$P_s(\text{dBm}) = -51 + 1 + 1.5 + L_f + 3$$

$$= 45.5 + L_f \text{ (no gain).}$$

$$P_s(\text{dBm}) = -62.5 + 1 + 1.5 + L_f + 3$$
$$= -57 + L_f \text{ (optimum gain).}$$

For simplicity, we shall first assume that we can use an LED source. From Chapter 2, we find that a nominal value of coupled power from an LED into a fiber with an NA on the order of 0.2 to 0.3 is 0.2 mW (-7 dBm). Using this value for P_s in the above, we find that the range for the allowable fiber loss, L_f, is 38.5 dB to 50 dB for the no gain and optimum gain case, respectively.

For a link length of 4 km, the value for the no gain case suggests that a fiber with an attenuation factor of 10 dB/km or less will be required for the no gain case. On the assumption that the power coupled into the fiber can be higher than the nominal value for a carefully selected source, we will first attempt a power-limited design using a PIN diode (no gain) detector and a SI fiber with a 10 dB/km attenuation factor (γ). If we find that we cannot increase the assumed coupled power from a LED source, we will then have to make a choice of selecting a higher-power source such as an LD, use an APD detector with gain, or select a fiber with lower attenuation.

(8) Source and fiber coupling geometry.

At this point in the design procedure we have the option of tentatively selecting either a particular fiber and then finding a source that will provide the best match for power coupling, or select a source and compute the coupling parameters required for the fiber. Since we have already specified that the fiber we select will be a SI type with $\gamma \cong 10$ dB/km, it is probably logical to choose this component first and then seek an LED source suitable for the fiber. This option has the advantages of permitting some cost comparisons for available fibers (which will dominate the system costs), and perhaps a wider choice in source selection. From this choice of fiber, the required source power from (7) above becomes

$$P_s = -5.5 \text{ dBm (0.28 mW) no gain}$$
$$= -17 \text{ dBm (0.02 mW) optimum gain.}$$

We note from the fibers listed in Table 2-10 that there are several commercially available SI fibers with the attenuation factor above. The cost estimates of these span a fairly broad range. We will not use any actual cost estimates here, but merely call this consideration to the attention of the reader. Note that the appropriate fibers have NA values in the range of 0.16 to 0.25. Our next step is to determine if these values are adequate in association with available LED's.

From Equation (2-16) we find that the NA of the SI fiber is proportional to the sine of the critical angle, ζ_c. Thus, for the NA values above, we find the value of the critical angle to be (for $n_o = 1$):

$$\zeta_c \leq 9° \quad \text{for NA} = 0.16$$

$$\zeta_c \leq 14° \text{ for NA} = 0.25 \quad .$$

From the discussion in both Chapters 2 and 6, we know that we have higher power-coupling efficiency with the larger NA values, and when the source radiation pattern approaches the acceptance cone of the fiber. The latter is, of course, related to the critical angle.

As an example of the source selection procedure, we refer to the LED's presented in Table 2-3. Note that the first three entries of the table (two shaped-geometry sources and one edge emitter) have emission (one-half power) angles that are less than the critical angle values found above for the SI fibers. The first source of the table has the smallest emission angle, given as $\pm 2°$, and also produces the highest radiant intensity of the three. This particular source uses an epoxy lens to shape the radiation pattern, and requires careful positioning of the fiber for optimum coupling. The radiation pattern is smaller than our requirement, but it may have an advantage in dispersion characteristics (later on) in reducing the number of modes launched (modal dispersion). We will keep this source in mind when we evaluate the dispersion limits of our system.

The shaped (dome) geometry source, which is the second entry in Table 2-3, should provide a good match to the critical angle of the fiber since it has a half-power emission angle of $\pm 12°$. We will tentatively select this device for use, and complete our calculations for the power-limited operation.

(9) Incident power on the fiber core.

Equation (6-11) is next used to calculate the incident power on the core of the fiber. The equation is repeated here for convenience:

$$P_T = P_o\left[1-(\cos\phi)^{m+1}\right], \tag{C-4}$$

where P_o is the total radiated power, and m is a parameter of the source radiation pattern. Recall that ϕ in the expression becomes the critical angle of the fiber when a particular fiber is addressed.

Using the half-power radiation angle given in Table 2-3 for the dome-type LED of $\pm 12°$, we calculate the value of m in Equation (C-4) as

$$(\cos\phi)^m = (\cos 12°)^m = 0.5 \tag{C-5}$$

$$m \cong 31.$$

Thus, the incident power into a fiber with NA = 0.25 ($\zeta_c = 14.5°$) is found as

$$P_T = P_o\left[1-(\cos 14.5°)^{32}\right] \tag{C-6}$$

$$= P_o\left[1-0.355\right]$$

$$= 0.645\ P_o.$$

P_o for the non-Lambertian source is the total power radiated by the device. For the source we have selected for consideration in Table 2-3, P_o is given as 3 mW. Therefore

$$P_T = 0.645\ P_o = 0.645 \times 3 = 1.935 \text{ mW} \tag{C-7}$$

$$P_T \text{ (dB)} = 2.87 \text{ dBm}.$$

This result is seemingly large with respect to our initial premise in (7) above, i.e., that a nominal value of coupled power from an LED source is 0.2 mW. However, we have not yet taken into account a very important aspect of the coupling problem that is discussed in Chapter 6. That is the mismatch between the source radiating area and the area of the fiber core. It was stated in Chapter 6 that an additional coupling loss will result from this mismatch, that is proportional to the ratio of the two areas. The diameter of the SI fiber selected for this example is $a = 62.5\ \mu m$. The radiating spot diameter d_s of the dome-type LED is given in Table 2-3 as 2 mm. The loss due to this mismatch is found as

$$L_a = 10 \log \frac{a^2}{d_s^2} = 20 \log \frac{a}{d} \tag{C-8}$$

$$= 20 \log \frac{.0625}{2} = -30 \text{ dB.}$$

Thus, the result found in (C-7) must be modified by the area mismatch loss, and the values become

$$P_T(\text{dB}) = -30 + 2.87 = -27 \text{ dBm} \tag{C-9}$$

$$P_T = .002 \text{ mW} = 2\ \mu\text{W}.$$

Note that the result given by (C-9) is comparable to the tabulated value for the coupled power into a single fiber given in Table 2-3, for the dome-type LED. A fiber with $a = 50\ \mu m$ would yield a loss of 32 dB, and a final coupled power of 1.25 µW. The loss factor found in (C-8) is seen to be extremely important. It illustrates a misunderstanding that can easily arise when one considers the radiance or radiant intensity values given for various shaped-geometry or lensed sources. This result also points out the importance of the conservation of radiance concept discussed in Chapter 6.

The result of (C-9) indicates that the system power requirements cannot be met with the first LED choice. The power coupled

into the fiber is seen to be 10 dB lower than that required for the optimum gain case found in (C-3); it is 21.5 dB lower than that required for the no gain case. We must, therefore, consider a better source to meet the power budget.

(10) Selecting an optical source.

Without repeating the above computations for another source, we note from Table 2-3 that the Burrus type LED's offer a considerably higher coupled power into the single low-loss fiber. For example, the first entry in the table lists a coupled power of 20 nW. Following the same procedures as those in (9) above, it can be shown that this source is capable of coupling 50 nW (-13 dBm) into our selected fiber of a = 62.5 μm. Thus, in this case, we could select an APD detector that would supply the optimum gain computed in (3), and use the first Burrus LED of Table 2-3. The 50 nW coupled power would provide a power margin of 4 dB above the required, and the 3 dB derating factor which we included in (7) would provide an overall margin of 7 dB. This would be considered an adequate margin, in accord with the discussion in Chapter 6. The disadvantage of this solution is the requirement of an APD and optimum gain (see Chapter 2).

For simplicity and operational stability, a design that retains the PIN diode detector would be preferrable. An option that we can consider here involves an LED source such as the last entry in Table 2-3. The computed coupled power for this source (again using the steps in (9) above) into a 62.5 μm fiber is greater than 300 μW (-5.2 dBm). Note that this is very close to the value required for the no gain case found in (8). The selection of this source would thus provide the minimum power required, with only the 3 dB margin included for derating.

A final option that retains the PIN diode detector (no gain) and provides a much higher margin, is a configuration using a single repeater at mid path on the link. The fiber loss between the repeater and each terminal would be one-half the total, improving the power budget at each detector by 20 dB. Thus, the required coupled power into the (half length) fiber would be

-14.5 dBm (35.5 μW). From this result we note that the Burrus type LED with the lower power rating in Table 2-3 would be adequate. The coupled power for this source we computed previously to be 50 μW (-13 dBm). This design would provide a total power margin of 4.5 dB on each half of the link, between the repeater and each link terminal.

(11) Summary of the power limited case.

In the above discussion of the power limited regime, we have seen that it is possible to design a digital link on the order of 4 km in length using only LED sources and PIN detectors. Other options have introduced detector gain (APD) and the use of repeaters to balance the power budget for different selections of the terminal devices. Before the final selection of any option is made, the designer must consider the other factors involved. These include the system costs, reliability, maintainability, and the impact of the secondary design features that might be required to optimize these factors. We include in the latter for example, the special circuitry that may be required to stabilize the gain of an APD with temperature changes.

Another component option that has been neglected to this point is that of selecting an LD source. The coupled power from these sources is generally much higher than the LED, but they also require more complexity in application. Their greatest advantage is often found to be in the dispersion limited regime, where the spectral width of the source and speed become important. These devices are considered below for the dispersion-limited discussion of our design problem.

b. <u>Dispersion Limit Calculations</u>

The next step of the design procedure (again following Table 6-1) is to evaluate the dispersion limits for the components and fiber selected above for the power limited options. To begin this process, we shall use the total distributed dispersion factor furnished by the manufacturer of the fiber. As noted in Chapter 6, the conditions under which this dispersion factor has been measured

are not often known. Therefore, the term should be used only as a first approximation in determining the dispersion limits for a particular design problem. If the results obtained indicate a borderline situation, a more detailed analysis should be carried out. Approximate equations for the dominant dispersion terms are given in Chapter 6, and specific expressions are treated in Appendices A and B. In each instance, more information regarding the fiber and source characteristics may be required. The designer may have to seek this additional information from the manufacturer.

(1) Allowable data rate.

The first step in the dispersion limit computations is to determine the possible data rate for the configuration(s) considered in the power limited design. The allowable bit rate is a function of the pulse spread caused by dispersion, and is given by Equation (6-20) or the "figure of merit" form of Equation (6-22). For the SI fiber selected above, the manufacturer specifies a dispersion factor $\Delta\tau = 30$ ns/km. Thus, the figure of merit becomes

$$R \cdot L = \frac{1}{2\Delta\tau} = \frac{1}{2 \times 30 \times 10^{-9}} = 16.67 \text{ Mb/s} \cdot \text{km} . \qquad \text{(C-10)}$$

For the specified bit rate of 10 Mb/s, we immediately see that the fiber selection would limit the allowable link length to a value slightly greater than 1.5 km. For our required 4 km length, the allowable bit rate would be on the order of 4 Mb/s. It is obvious from this result that our initial design is limited by dispersion, due to the fiber characteristics alone. Thus, at this juncture, we must consider some design changes and options. These can be conceptual changes and/or component changes. A few options are discussed below.

(2) Addition of repeaters.

The figure of merit found above indicates that the selected SI fiber will provide adequate performance within the dispersion

limit if repeaters are used at intervals of approximately 1.5 km. A total of two repeaters would be required, and the system configuration would be as sketched in Figure C-1.

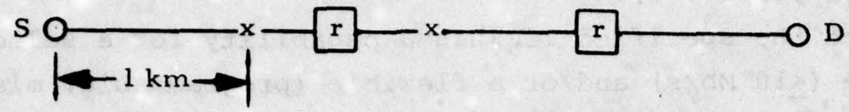


Figure C-1. Illustration of configuration with SI fiber and repeaters.

This obviously will double the cost of the source and detector components, as well as the cost of the repeater installations and equipment. Complexity is also added in the sense that power must be provided at the repeater locations, and maintenance of the repeaters will be required in the system operation.

At least part of the cost differential for this option can be offset by a change in component selection. Since we are considering the same source and detector (optical) as originally selected, we can relax the attenuation requirements for the optical fiber. The required power at each detector is based on a fiber length of 1.5 km (max) as opposed to 4 km in our original (repeaterless) configuration. Thus, the attenuation factor can be more than twice the value of the original fiber choice, which was 10 dB/km. As an example, Table 2-10 lists a fiber with the same dispersion and NA characteristics as the one originally selected, but with an attenuation factor of 20 dB/km. The designer should compare the relative costs of these two fibers (or others with similar properties) with the costs involved with the two repeater stations in Figure C-1 to completely evaluate this design option.

(3) Change in data rate or baseband structure.

Another conceptual design change can be made on the basis of the data rate, R, or the formatting of the mission signal. The

latter option is one that is related to the particular modem we are considering in this example; namely, the interconnect facility (ICF) noted in the specifications for this sample problem (Section C-1).

Since the specified ICF has a capability for a selectable data rate ($\leq$10 Mb/s) and/or a flexible (programmable) mission bit stream, both of these factors permit viable options. First, it is conceivable that the overall mission of the link may be met using a lower data rate, R. Note from the result found from Equation (C-10) that the original design will perform adequately at a data rate of approximately 4 Mb/s. The designer must weigh this option against the overall mission requirements of the link, including perhaps future expansion needs.

A variation of the above option that should also be considered is the application of SDM in the fiber-cable structure. For example, the original SI fiber considered could be used at this lower data rate, with multiple fibers in the cable structure. In this case, the total mission bit-stream could be configured in the ICF to provide two or three separate data streams (4 Mb/s or less) on each fiber. In this manner, the combined mission bit rate would be 8 Mb/s to 12 Mb/s, respectively. This alternative (obviously) again increases the number of optical sources and detectors (as well as the number of fibers), but eliminates the requirement for repeaters. The economics for such a tradeoff may be in favor of the repeaterless design.

(4) Component changes.

We have seen from consideration of the above options that the design of our system must be compromised in some conceptual manner to accommodate most step-index fibers. If it is not possible to meet the mission requirements of the link with any of those options, then the designer must begin to consider changes in component selection.

Under the assumption that the optical source and detector (finally selected) will each have an adequate switching speed for

the desired transmission rate (bit rate), then the only component change that can be made to improve the dispersion limit is the choice of fiber. Also assuming at this point that the dominant dispersion is caused by mode dispersion, then the first logical change in fiber selection would be to consider a graded index fiber. The choice would be made among fibers having attenuation factors that were nearly the same as those used in the power limited computations, but with much lower dispersion factors. These choices are illustrated in the following sections.

Before we discuss the selection of a graded index fiber, however, an important additional power-loss term must be recognized, that will impact on the power limit computations made previously. It was pointed out in Chapter 6 that the coupling efficiency from a given source into a graded index fiber is less than that for the comparable step index fiber. The loss encountered between the two cases depends upon the profile parameter (see Appendix A) of the graded index fiber, and is given in Figure 6-5. For example, referring to the figure, we find an additional coupling loss of approximately 4 dB for a graded index fiber whose profile parameter $\alpha = 2$. With respect to some of the power limit margins found in Section C-3, we note that this loss can be significant. It must be added into all previous options for the power limited computations.

(5) Selection of a graded-index fiber.

Since we have seen that our initial design is dispersion limited using a SI fiber, our next step is to consider a GI fiber with essentially the same attenuation factor and NA. Table 2-10 lists two GI fibers, each with an attenuation factor of 10 dB/km. One fiber lists a dispersion term of 5 ns/km, and the other 3 ns/km. Each of these has a slightly smaller NA than the SI fiber we have been considering; they are 0.2 and 0.18 respectively. This difference will introduce still another loss of approximately 1.5 dB in the power-limited computations, which must be added to the design options in Section C-3a.

The above dispersion factors will yield a total spread of 20 ns and 12 ns respectively, over the 4 km length of the fiber. Using Equation (6-9) with these dispersion factors, the new figure of merit for the link becomes:

$$\begin{aligned} R \cdot L &\le 100 \text{ Mb/s} \cdot \text{km (for the 5 ns/km fiber)} \\ R \cdot L &\le 166.6 \text{ Mb/s} \cdot \text{km (for the 3 ns/km fiber} \end{aligned} \qquad \text{(C-11)}$$

and the dispersion limit parameters are

$$R \le \begin{cases} 25 \text{ Mb/s for the 5 ns/km fiber} \\ 41.6 \text{ Mb/s for the 3 ns/km fiber} \end{cases} \quad (L = 4 \text{ km})$$

$$L \le \begin{cases} 10 \text{ km for the 5 ns/km fiber} \\ 16.6 \text{ km for the 3 ns/km fiber} \end{cases} \quad (R = 10 \text{ Mb/s}) \; .$$

These results indicate that the choice of either of these GI fibers will fulfill the design requirement for any repeaterless configuration.

It is important at this point, however, to reconsider these values with respect to another (specific) operational requirement of the system. For this design example, we established an initial requirement that the system was to work within the specifications given for an interconnect facility (ICF) in Chapter 4. These specifications include a rather stringent requirement on the integrity of the rise and fall times (T_r and T_f) of the signal pulse. The specification is repeated below as

$$\begin{aligned} &4 \text{ ns} < T_r \text{ and } T_f < 12 \text{ ns (for channel bit rate)} \\ &100 \text{ ns} > T_r \text{ and } T_f \quad \text{(for strapped channels)}. \end{aligned} \qquad \text{(C-12)}$$

Since the dispersion factor of the transmission fiber will affect the rise and fall times of the optical pulse just as it does the delay spread (or pulse width), this specification can become the most critical to our design.

For example, we note that the GI fiber above with the smallest dispersion factor (3 ns/km) would increase the rise and fall times of the pulse a total of 12 ns over the 4 km fiber length. This is seen to be the upper limit of the allowable range given by (C-12). A fiber with a higher dispersion factor

will not meet the specification at all for the channel bit rate. However, if it is planned to use the ICF in a strapped configuration, either of these fibers will suffice.

In Chapter 6, we cautioned the reader about accepting the manufacturers dispersion terms at face value. It is usually not clear under what conditions the specified term was obtained, and thus in borderline situations more information is required. Such is the case here; the computed rise time for the 3 ns/km fiber would equal the upper specified bound for the ICF for the desired channel bit rate. If this is an absolute requirement for the overall system, then additional work is required. There are a number of options available, which are discussed in the following sections.

(6) The graded-index fiber with repeaters.

Just as in some of the previous options treated, we can consider a design that includes one or more repeaters. The function of the repeater in this case is not to overcome the power limit or the basic pulse spread, but to reshape the transmitted pulse at required intervals so that the rise and fall times will remain within the limits required for an ICF. If we select a nominal range of values of rise and fall times within the specified limits of (C-12) (4 to 12 ns) as 6 to 10 ns, then either of the GI fibers above could be used with a single repeater located at approximately mid-path (2 km). The change in rise and fall time of the pulse transmitted over the first half of the link would be electronically corrected by regenerating the data and clock stream in the repeater. This is discussed further in the following section.

(7) Source and detector speed.

Up to this point in all of our design steps, we have assumed that the source and detector speed was adequate, and the limit on switching time would be due to the fiber dispersion. This would generally be true for the bit rate performance criteria, as the speed factors for both the LED and the PIN diode are fast enough

for the bit rate we have considered. However, this factor adds a complexity to our problem with respect to the rise and fall time requirements discussed in (5) above. For example, we again turn to Table 2-3 and note that the speed factors listed for the LED sources in this table range from 10 to 15 ns. It is obvious that most of these sources would not meet the ICF requirement for rise and fall time integrity, even without the added fiber dispersion. In comparison, the speed factors for the PIN diodes of Table 2-7 are seen to be much smaller than those for the LED's; they range from 0.5 ns to 6.5 ns. Thus, the detector speed is not as critical but it must be considered in the overall problem.

In (6) above, we have suggested that the increase in rise and fall time, due to fiber dispersion and the optical components, might be electronically corrected. This would be accomplished by regenerating the signal pulse in electronic circuits. It is possible to do this either in the repeater circuits, or in the electronics which generally follow the optical detector, or both (see Chapter 5). However, in the case of the ICF, an additional requirement must also be considered, and that is the relative timing stability between the data and clock signals. This specification is seen in Figure 4-4. Since the data and timing signals will (in most instances) require separate fibers in the optical transmission system, the fibers, optical components, and the electronic circuits must be well matched in order to maintain the timing relationship.

Even though it may be possible to compensate for the increase in rise and fall times of the optical pulse in the electronic circuitry, it is important to minimize this dispersion affect in the optical link. Thus, in the design problem involving the ICF, a step that should be taken to reduce the dispersion is to select an LD source in place of the LED's that have been considered. The LD, in general, will provide greater coupled power, and the switching speed of the device is considerably faster. We will also discuss another significant advantage in the following section.

(8) The graded-index fiber with selected parameters.

The final design option for our proposed system involves a greater attention to operational parameters, if the conceptual design precludes the use of repeaters. We found in (5) above, using a GI fiber with a specified dispersion term as low as 3 ns/km, that the rise and fall time required for an ICF interface was a borderline situation. The fiber alone would distort the rise and fall times to approximately 12 ns over the 4 km link without repeaters. This value was also seen to be the upper bound on the ICF specification. Thus, in order to meet this requirement in the optical system, we must look closely at the options involved with the specific fiber and its operational parameters.

The techniques required to analyze this option are those outlined and discussed in Appendix B for the long-haul system. For example, in the design problem discussed here (for the relatively short link) we began with an arbitrary selection of an operating wavelength of 850 nm, and the spectral width of our selected LED source was given as 20 nm. We, of course, have the option of changing either or both of these parameters. In order to illustrate the potential improvement possible, we will use the results given in Appendix B. We will not follow a detailed analysis of these options, as the example in Appendix B has been presented to convey these details.

Referring to the figures of Appendix B, we note that significant improvement in total dispersion in the GI fiber can be achieved with proper attention to wavelength, the profile parameter of the fiber, and the fiber material. In varying or carefully selecting these parameters, we are attempting to change the operational characteristics of the total system in such a way as to approach the material dispersion limit of the fiber, as discussed in Chapter 6.

The first important characteristic is illustrated in Figure B-1. Note that there is little change in the dispersion for the GI fiber operating with a source having a spectral width

that is typical of the LED ($\Delta\lambda$ = 30 nm), over a rather broad range in the profile parameter, α. However, if we select a source such as an LD with a spectral width on the order of 3 nm, the dispersion curves for the sample fibers in Figure B-1 show that a factor as low as 0.4 ns/km should be attainable with optimum values of the profile parameter (approximately 1.95 and 2.5 for the samples shown). This is nearly an order of magnitude lower in dispersion than the graded index fibers that we discussed in (5) and (6), and the subsequent improvement in the system performance would be dramatic. The fiber would no longer be the limiting component for the rise and fall times of the optical pulse, and the ICF signal integrity could easily be met with proper selection of source and detector speed. Note also from Figure B-1 that by simply selecting an LD source in place of an LED (reducing spectral width), would provide an improvement in fiber dispersion by a factor of at least 3 regardless of the optimum profile parameter. This result in itself is sufficient to conclude that the design requirement for the ICF can be met in the optical system with *proper consideration* of the properties of the graded index fiber. The designer must obtain additional information from the manufacturer, however, in order to assure these expected improvements. Again, the reader is referred to Appendices A and B for the details of the procedures to follow.

A less dramatic improvement in dispersion properties of a graded index fiber should also be observed. For example, the curves given in Figures B-3 and B-4 show the fiber dispersion factor as a function of wavelength for a fiber having an optimum profile. Note at the shorter wavelengths of interest here (800 to 900 nm) that a slight improvement in dispersion can be obtained by increasing the operating wavelength. For example, in the design problem discussed throughout this appendix, we arbitrarily selected an operating wavelength of 850 nm. The curves in Figure B-3 indicate that an improvement in fiber dispersion of approximately 1 ns/km could be achieved by operating at 900 nm. This is a small improvement, but when applied to the total link

length of 4 km it would reduce the dispersion by 4 ns. This is a significant change with respect to the rise and fall time dispersion for the ICF. The resulting improvement would remove the borderline situation in (5) above. The dispersion caused by the fiber in this case would be held within the bounds speficied for the ICF.

C-4. SUMMARY

This appendix has discussed a fairly specific design problem, to illustrate the use of the material and procedures presented in the handbook. The example problem treats the case of a relatively short optical-fiber link design, but it includes specifications for an interface to a specific communication system. The latter is used to illustrate more detailed design considerations that are encountered frequently in total system design concepts.

In the discussion presented, we have not specifically repeated the iterative design process that is illustrated by Table 6-1. However, we have followed this flow diagram through both the power limited case and the dispersion limited case, and discussed the various options available at critical points in both procedures. To indicate how the process does actually become iterative in the flow diagram of Table 6-1, we have pointed out the impact that particular design choices or component selections that are made in one design mode will have on the other. These matters have been restricted (for the most part) to the technical impact, with only passing notice of the economic (cost) impact, and other operational features implied by the various options presented. When the system designer takes these important factors into account, the iterative nature of the design problem becomes even more apparent.

To summarize the design problem presented, we have concluded the following:

1. A system composed of a step-index fiber, an LED source, and a PIN diode detector can be configured to meet the power limited requirements over a 4 km link.

2. Care must be exercised in selecting the appropriate LED source. The computations show that for shaped geometry sources, even though they have high radiant intensity values and good geometric properties with respect to the fiber, the coupled power losses are extremely high. The significant factor is the mismatch of the emission area with respect to the fiber core area. Total radiance is the most important characteristic.

3. The Burrus type LED provides the best power coupling to the single low-loss fiber needed for the link.

4. The use of both repeaters and/or detector gain (APD) were considered as options at certain design points. However, these options were discounted as optimum due to the added complexity of the operational and maintenance requirements.

5. The graded index fiber was found to be necessary to meet the dispersion limit requirements. This type of fiber together with a Burrus type LED were found adequate for the desired bit rate of 10 Mb/s. However, additional power losses on the order of 6 dB required the selection of a higher power LED than that required for the step index fiber.

6. Although the combination of a graded index fiber and a high power LED met the bit rate requirements, the dispersion was still found to be excessive with respect to rise and fall times of the optical pulse. The requirement on this parameter was established by the specifications of the interconnect facility (ICF) assumed as the communication system to be used.

7. A graded index fiber driven by an LD source with a narrow spectral width on the order of 3 nm was found to meet all of the dispersion limits of the system. This combination would also exceed the

system power budget, and thus permit the system to operate nearer the dispersion limits; a recommendation made in Chapter 6.

GLOSSARY OF TERMS

ABSORPTION (COEFFICIENT): Characterizes the conversion of light (or other electromagnetic energy) into energy of other forms (e.g., heat) as it traverses a continuous medium, thus causing a diminution of the incident beam. The absorption coefficient has dimensions of $(\text{length})^{-1}$. The absorption coefficient of a given material may depend on frequency, and is sharply peaked near a resonant absorption.

ACOUSTO-OPTICS: The study of the interactions between sound waves and light in a solid medium. Sound waves can be made to modulate, deflect and focus light waves - an important factor in laser applications.

ACTIVE MEDIUM: The material - such as crystal, gas, glass, liquid or semiconductor - which actually "lases". Also called laser medium, lasing medium, and active material.

AMPLITUDE: The amplitude of a light wave is the strength of the electric field of the wave. The amplitude of the wave differs from the intensity, since the latter measures the power in the beam and is proportional to the square of the amplitude. Particularly, the complex amplitude of a wave is a two dimensional vector whose length is equal to the wave amplitude and whose direction measures the phase. When two waves are superposed, their complex amplitudes add vectorially. Hence, two waves with the same phase combine to form a wave of larger amplitude, while two waves which are out of phase may cancel. Such reinforcements and cancellations are called interference effects.

ANGLE OF REFLECTION: The angle formed between the normal to a surface and the reflected ray. This angle lies in a common plane with the angle of incidence and is equal to it.

ANGLE OF REFRACTION: The angle formed between a refracted ray and the normal to the surface. This angle lies in a common plane with the angle of incidence. See Snell's Law of Refraction.

ANGSTROM UNIT: Unit of length equal to 10^{-10} meter. Not an international standard (SI) unit.

ANTIREFLECTION COATING: A thin layer or film applied to an optical surface to reduce the reflectance and to increase the transmittance. The ideal value of the refractive index of a single-layered film is that of the square root of the product of the refractive indices on either side of the surface to which it is applied, the ideal optical thickness being one quarter of a wavelength.

ATTENUATION: The reduction in light intensity that results when the light travels through an absorbing or scattering medium.

ATTENUATION COEFFICIENT: The sum of the scattering and absorption coefficients.

AVALANCHE PHOTODIODE (APD): A photodiode designed to take advantage of avalanche multiplication of photocurrent. As the reverse-bias voltage approaches the breakdown voltage, hole-electron pairs created by absorbed photons acquire sufficient energy to create additional hole-electron pairs when they collide with substrate atoms; thus a multiplication effect is achieved.

BANDWIDTH: The range of frequencies over which an instrument or device is designed to function within specified limits.

BEAM DIAMETER: The distance between the two points at which the power density or energy density of the beam is a specified fraction (typically 1/2, 1/e, $1/e^2$ or 1/10) of the peak density.

BEAM DIVERGENCE: The increase in beam diameter with increase in distance from the appropriate aperture. Divergence, expressed in milliradians, is measured at specified points - usually where power density or energy density is 1/2 or $1/e^2$ the maximum value; can be specified as half-angle or full-angle divergence.

BEAM WIDTH (ANGULAR BEAM WIDTH): The angular beam width of a cone shaped light beam is the vertex angle of the cone. It measures the rate at which the beam diverges or converges. The minimum beam width of an optical element is determined by its aperture. In radians, the minimum beam width is approximately λ/A where λ is the wavelength and A the aperture dimension. No optical device can have a beam width less than this.

BER: Acronym for bit error rate.

BIREFRINGENT MEDIUM: If light traversing a medium can be decomposed into two perpendicular directions of polarization which travel at different velocities, the medium is said to be birefringent.

BLACK BODY: This term denotes a perfectly absorbing body. It reflects none of the incident energy.

When in thermal equalibrium, a black body absorbs (perfectly) and radiates (perfectly) at the same rate; the radiation will be just equal to absorption if thermal equalibrium is to be maintained.

The spectral energy density of black body emission is the theoretical maximum for a body in thermal equilibrium. Black body radiation is caused by the radiation from a large number of independent, incoherent electromagnetic oscillators in thermal equilibrium; hence, it is quite different from laser radiation, whose source oscillators are vibrating in concert (i.e., coherently).

BOLTZMANN'S CONSTANT (k): 1.38×10^{-23} joules/^{0}K.

BRIGHTNESS: A term used in nonquantitative statements, especially with reference to sensations and perceptions of light. Brightness is an attribute of visual perception in accordance with which a source appears to emit more or less light; since the eye is not equally sensitive to all colors, brightness is not a quantitative term.

BUNDLE: Several (optical) fibers grouped loosely together, usually without a separate strength member.

CABLE (FIBER OPTICAL): A cable is a jacketed bundle or jacketed fiber in a form which can be terminated.

CABLE ASSEMBLY: A cable which is terminated and ready for installation.

CARRIER INJECTION: The process whereby light is emitted at the junction of n- and p-type semiconductors when an external electric source is applied to drive the electrons and the holes into the junction.

CLADDING: Material that covers the fiber core and provides optical insulation and protection for the core; also called the coating.

CLADDING MODE STRIPPER: Material applied to the fiber cladding, providing a means for allowing light to leave the cladding of the fiber.

COHERENCE: A word used to denote various forms of temporal or statistical phase correlations of electromagnetic fields at different spatial positions; the more extensive the correlations, the greater the coherence. In a beam of radiation there will always be certain random fluctuations in the phase difference of the fields at two separate points; these fluctuations normally increase as the separation of the points increases. "Coherence distance" in a beam is the distance between points for which the average of this random phase difference is less than about one radian; it often is different for points spaced along or transverse to the beam axis. "Coherence time" is specifically the time light takes to travel the coherence distance in the beam direction

(i.e., propagation direction). If fields from regions separated by less than the coherence distance are superposed as by splitting the beam and recombining it in various ways, interference effects result which are not averaged to zero by the random fluctuations.

COHERENT BUNDLE: A bundle of fibers in which the coordinates of each fiber are the same at the two ends of the bundle; also referred to as an aligned bundle.

COHERENT RADIATION: Radiation in which the phase between any two points in the radiation field has a constant difference, or is exactly the same throughout the duration of the radiation.

COLLIMATION: The process by which a divergent beam of radiation is converted into a parallel beam.

CONDUCTION BAND: A partially filled or empty energy band in which electrons are free to move easily, allowing the material to carry electric current.

CONSERVATION OF RADIANCE: Formally called the conservation of brightness. A basic principal which states that optical paraphernalia cannot increase the radiance of a source; the radiance of an image cannot exceed that of the object.

CORE: The central region of a fiber. The refractive index of the core must be higher than that of the cladding, in a fiber waveguide.

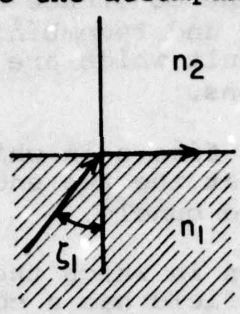
COSINE EMISSION LAW: Also called Lambert's emission law; an expression which relates the magnitude of emission of energy to the angle relative to the radiating surface. In particular, the cosine law specifies that the energy emitted in any direction is proportional to the cosine of the angle which that direction makes with the normal to the emitting surface. Emitters which radiate according to this law are referred to as Lambertian sources.

CRITICAL ANGLE: Basically, the least angle of incidence at which total reflection takes place. The angle of incidence in a denser medium, at an interface between the denser and less dense medium, at which the light is refracted along the interface. When the critical angle is exceeded, the light is totally reflected into the denser medium. The critical angle varies with the indices of refraction of the two media with the relationship,

$$\mathrm{Sin}\ \zeta_1 = \frac{n_2}{n_1}$$

where ζ_1 is the critical angle; n_2 the refractive index of

the less dense medium; and n_1 the refractive index of the denser medium. See the accompanying figure.



DARK CURRENT, I_d(A): The current that flows in photosensitive detectors when there is no incident radiant flux (total darkness).

DETECTIVITY, D(W^{-1}): Reciprocal of noise equivalent power: D=1/NEP.

DETECTOR NOISE LIMITED OPERATION: Used to denote operation when the amplitude of the pulse, rather than its width, limits the distance between repeaters. In this regime of operation, the losses are sufficient to render the amplitude of the pulse too small to allow an intelligent decision on the presence or absence of a pulse.

DICHROIC FILTER: A filter used to selectively transmit light according to its wavelength and not its plane of vibration.

DICHROIC MIRROR: A mirror used to selectively reflect light according to its wavelength and not its plane of vibration.

DIFFERENTIAL QUANTUM EFFICIENCY (DIMENSIONLESS): Used in describing quantum efficiency in devices having non-linear output-input characteristics; the slope of the characteristic curve is the differential quantum efficiency.

DIFFRACTION: Deviation of light from the paths and foci prescribed by rectilinear propagation (geometrical optics). Thus, even with a very small, distant source, some light, in the form of bright and dark bands, is found within a geometrical shadow because of the diffraction of the light at the edge of the object forming the shadow. Because of diffraction, the ideas of a light ray, a point or sharp edge image, or a parallel beam, are only approximately valid. Light can only be focused to a spot of the order of a wavelength in diameter and a "perfectly" collimated light beam of finite aperture always diverges into its minimum beam width. These effects are called diffraction effects. If light is repeatedly reflected between mirrors of finite aperture, some light always strays past the mirror edges; this loss of light energy from the resonator is called diffraction loss.

DIFFRACTION GRATING: An array of fine, parallel, equally spaced reflecting or transmitting lines which mutually enhance the effects of diffraction at the edges of each so as to concentrate the diffracted light very close to a few directions characteristic of the spacing of the lines and the wavelength of the diffracted light. If i is the angle of incidence, d the angle of diffraction, s the center-to-center distance between successive rulings, n the order of the spectrum, the wavelength is

$$\lambda = (s/n)(\sin i + \sin d).$$

DIODE LASER: See semiconductor laser.

DISPERSION: A term used to describe the frequency dependence of a parameter. The term can be used, for example, to describe the process by which an electromagnetic signal is distorted because the various frequency components of that signal have different propagation characteristics. The term is also used to describe the relationship between refractive index and frequency (or wavelength).

DISPERSION LIMITED OPERATION: Used to denote operation when the dispersion of the pulse, rather than its amplitude, limits the distance between repeaters. In this regime of operation, waveguide and material dispersion are sufficient to preclude an intelligent decision on the presence or absence of a pulse.

DUTY FACTOR, PULSE (DIMENSIONLESS): The ratio of average pulse duration to average pulse spacing.

D-STAR, D* (W^{-1} m $Hz^{1/2}$): Detectivity multiplied by the square root of the detector area and the square root of the detector bandwidth.

EFFICIENCY: See quantum efficiency, differential quantum efficiency, power efficiency.

ELECTROLUMINESCENCE: Direct conversion of electrical energy into light. One example involves the photon emission resulting from electron-hole recombination in an p-n junction. This is the mechanism involved in the injection laser.

ELECTRONIC CHARGE (q): 1.6×10^{-19} coulomb. Some authors use e as the symbol.

ELECTRO-OPTIC: Referring to devices whose operation relies on modification of a materials' refractive index by electric fields. In a Kerr cell, the index change is proportional to the square of the electric field, and the material is usually a liquid. In a Pockel's cell, the material is a crystal whose index change is linear with the electric field.

ELECTRO-OPTICAL DETECTOR: A device that detects radiation by utilizing the influence of light in forming an electrical signal.

EMISSIVITY: Ratio of flux radiated by a substance to the flux radiated by a black body at the same temperature. Emissivity is usually a function of wavelength. See also the definition of a black body.

ENERGY DENSITY: A beam's energy per unit area, expressed in joules per square meter.

FERMAT'S PRINCIPLE: Also called the principle of least time; a ray of light traverses that path which requires the least time. Stated another way, the optical path (see optical path length) is an extremum, in the terminology of the calculus of variations.

FDM: Acronym for frequency division multiplex; in optical communications, one also encounters wavelength division multiplex (WDM); WDM involves the use of several distinct optical sources (lasers), each having a distinct center frequency. FDM may be used with any or all of those distinct sources.

FIBER: A single discrete optical transmission element usually composed of a fiber core and a fiber cladding.

FIBER SHEATH: The word "sheath" is a general term used variously to mean cladding, buffer, or jacket.

FLUX: Time rate of flow of energy; the radiant power in a beam.

FLUX DENSITY: Flux per unit area measured normal to the direction of propagation.

FRESNEL REFLECTION: When light is incident upon the surface between materials of different optical indices, part of the light is reflected. This Fresnel reflection depends upon the index difference and the angle of incidence; it is zero at Brewster's Angle for one polarization. In optical elements, a thin transparent film is sometimes used to give an additional Fresnel reflection which cancels the original one by interference. This is called an anti-reflection coating.

GAIN-BANDWIDTH PRODUCT (OF AN AVALANCHE PHOTODIODE): The gain times the frequency when the device is biased for maximum obtainable gain.

GAUSSIAN SHAPED PULSE: A pulse which has the shape of a Gaussian or normal distribution. In the time domain, the shape is $f(t) = A \exp(-\xi t^2)$ where A and ξ are constants in time. A similar expression would hold in the frequency domain with t replaced by ν.

GEOMETRIC OPTICS: A field in physics that deals with light as if it truly were composed of rays diverging in various directions from the source and abruptly bent by refraction or turned back by reflection into paths determined by familiar laws. The concept that light travels in a straight line is the basis of geometric optics which neglects diffraction and acknowledges the wave theory of light only insofar as the wavelengths affect the refractive index. A system of optics derived by the assumption of zero wavelength.

GRADED INDEX PROFILE: The condition of having the refractive index vary continuously and smoothly between two extremes.

INCOHERENT: A lack of coherence. If there is no fixed phase relationship between two waves, they are said to be incoherent. If two incoherent waves are superposed, there are no interference effects which last longer than their individual coherence times. For light other than laser light these times are almost invariably too short to give an observable effect. Two laser beams which are individually quite coherent are nevertheless mutually incoherent if they originate from independent oscillators. However, if their individual coherence times are long, interference effects such as beats are readily observable.

INDEX OF REFRACTION: See refractive index.

INFRARED (ABBREVIATED, IR): The band of electromagnetic wavelengths between the extreme of the visible part of the spectrum (about 0.75 μm) and the shortest microwaves (about 1000 μm). The IR region is sometimes subdivided as follows:

Designation	Wavelength(μm)
Near infrared	0.75 - 3
Middle infrared	3 - 30
Far infrared	30 - 1000.

INJECTION LASER: An optical oscillator or amplifier employing as the active medium a forward biased semiconductor diode in which a population inversion has been established between the conduction band and valence band.

INTEGRATED OPTICS: That part of optical technology concerned with the interdependence of optical components. The elements of integrated optics are notable because they all function as a single unit or process and become useless if separated from the main body.

IRRADIANCE (watts/m^2): The power per unit area incident upon a surface. Also called radiant flux density.

LAMBERTIAN SOURCE: An emitter which radiates according to the cosine emission law.

LASER (MASER): An acronym for Light Amplification by Stimulated Emission of Radiation. It is derived from the older term maser, which substitutes Microwave for Light. The names are used to denote devices (in their respective frequency ranges), which utilize an active medium either to amplify incoming electromagnetic radiation, or to maintain a steady oscillation in a mode (or in at most a few modes) of a resonator. In this last role the laser acts as a generator of very coherent radiation. By common usage the term laser is applied also when the radiation lies in the infrared. Lasers fall into various classes according to the active medium and the method of exciting it.

LASING MEDIUM: Within a laser, the material that emits coherent radiation.

LED: Acronym for Light Emitting Diode.

LIGHT: For our purposes, radiant energy of wavelengths from about 0.3 μm to 30 μm; this includes visible wavelengths (0.38 μm to 0.78 μm) and those wavelengths, such as ultraviolet and infrared, which can be handled by optical techniques used for the visible region. In more restricted usage, radiant energy within the limits of the visible spectrum.

LIGHT-EMITTING DIODE (LED): A p-n junction device that radiates when biased in the forward direction.

MAGNETO-OPTICS: The study of the effects of a magnetic field on specific properties of light, such as polarization.

MATERIAL DISPERSION: That part of the total dispersion attributable to the fact that the material in question (glass, in the case of the glass fiber waveguide) has optical properties which change with frequency.

MERIDIAN PLANE: Any plane which contains the optical axis.

MERIDIONAL RAYS: A ray in a meridian plane.

MODE: The various possible patterns of standing waves of the electromagnetic field in an optical resonator are called modes. These modes are closely analogous to the modes of vibration of a violin string or a drumhead. They are characterized by their frequency and the spatial distribution of their polarization and field strength. The mode volume is a measure of the number of modes a structure will support. Microwave and optical transmission lines have modes, sometimes called transverse modes, which are field distributions over the cross section of the line.

MODE VOLUME: See mode.

MODULATION: The controlled variation of frequency, phase and/or amplitude of a carrier wave of any frequency in order to transmit a message. The modulation of a laser is a necessary step in its use in a communication system. Modulation does not affect coherence, which involves random phase fluctuations.

MONOCHROMATIC: A single frequency or wavelength. No radiation can be perfectly monochromatic, but will, at best, have a narrow band of wavelengths.

MULTIMODE FIBER: A fiber waveguide which will allow more than one mode to propagate.

MULTIMODE LASER: Simultaneous laser emission at several wavelengths.

MULTIPLEX: Putting two or more signals onto a single channel.

NOISE EQUIVALENT POWER, NEP(W): The rms value of optical power required to produce unity rms signal-to-noise ratio.

NUMERICAL APERTURE (NA): The usual definition is given as the meridional acceptance angle of a fiber, defined as

$$NA = \sqrt{n_1^2 - n_2^2},$$

where n_1 and n_2 are, respectively, the refractive index of the core and the cladding. When skew rays are included, the numerical aperture increases beyond the value given here. A more universal definition of NA is currently being sought. As a measure of light gathering ability of a fiber, this definition is not precise.

OPTICAL AXIS: The axis of symmetry of an optical system.

OPTICAL PATH LENGTH: In a medium of constant refractive index, n, the product of the geometrical distance and the refractive index. If n is a function of position

$$\text{Optical path length} = \int n\,ds,$$

where ds is an element of length along the path.

OPTICAL WAVEGUIDE: Any structure having the ability to guide the flow of optical energy along a path parallel to its axis and, at the same time, to contain the energy within or adjacent to its surface.

OPTOELECTRONIC DEVICE: A device which is responsive to electromagnetic radiation (light) in the visible, infrared, or ultraviolet spectral regions; emits or modifies noncoherent or coherent electromagnetic radiation in these same regions; or utilizes such electromagnetic radiation for its internal operation.

PACKING FRACTION: The fraction of cross-sectional area composed of the fiber cores in a fiber bundle assembly.

PARABOLIC PROFILE: Referring to the condition of having the fiber index of refraction vary in a parabolic fashion:

$$n(r) = n_1(1 - \Delta(r/a)^2),$$

where r is the radial distance from the fiber axis and Δ, a are constants; n_1 is the refractive index at r=0.

PARAXIAL RAYS: Rays which are nearly parallel with the optical axis. For purposes of computation, the angle between the rays and the optical axis is small enough for sin θ to be replaced by θ radians.

PHOTODIODE: A two-electrode, radiation-sensitive junction formed in a semiconductor material, in which the reverse current varies with illumination.

PHOTOELECTRIC EFFECT: This term originally referred to all changes in material electrical characteristics due to photon absorption. More recently, it is used to describe the emission of electrons as the result of the absorption of photons in a material. This definition is quite broad since the photons can be of any energy and the electrons can be released into a vacuum or into a second material. The material itself may be solid, liquid, or gas.

PHOTON: A quantum of electromagnetic energy. The energy of a photon is $h\nu$ where h is Planck's constant and ν is frequency. See Planck's law.

PLANCK'S CONSTANT: See Planck's law.

PLANCK'S LAW: The fundamental law of quantum theory, of basic concern in optical communications, which describes the essential concept of the quanta of electromagnetic energy. According to this law, the quantum of energy associated with an electromagnetic field of frequency ν is

$$E = h\nu,$$

where h is Planck's constant ($h=6.626\times10^{-34}$ joule sec) and E is the photon energy. The product of energy x time is sometimes referred to as "action". Hence, h is sometimes referred to as the elementary quantum of action.

POLARIZATION: The term used to describe the orientation (in space) of a time varying electric or magnetic field vector (including the field vector of an optical signal).

POWER: Energy per unit time.

POWER, AVERAGE: In a pulsed laser, the energy per pulse (joules) times the pulse repetition rate (hertz). Expressed in watts.

POWER, PEAK: In a pulsed laser, the maximum power emitted.

POWER DENSITY: Power per unit area (watts per square meter).

POWER EFFICIENCY (DIMENSIONLESS): The ratio of emitted optical power of the source to the electrical input power.

PULSE LENGTH: The time duration of the burst of energy emitted by a pulsed laser; also called pulse width or pulse duration. Usually measured at the "half-power" points (0.707 times the full amplitude of a voltage or current pulse).

QUANTUM EFFICIENCY, η (DIMENSIONLESS): A measure of the efficiency of conversion or utilization of optical energy, being the number of events produced for each incident quantum.

QUANTUM-LIMITED OPERATION: Operation wherein the minimum detectable signal is limited by fluctuations in the average signal current itself.

QUANTUM NOISE: See shot noise.

RADIANCE: Also called emittance; radiant flux (watts) per unit solid angle per unit of projected area of the source. The units are watts/m^2/steradian.

RADIANT ENERGY: Energy (joules) which is transferred via electromagnetic waves; there is no associated transfer of matter.

RADIANT EXITANCE (W/m^2): Radiant power emitted into a full sphere (4π steradians) by a unit area of source.

RADIANT FLUX: The time rate of flow of radiant energy. The units are watts.

RADIANT INTENSITY (watts/steradian): The time rate of transfer of radiant energy per unit solid angle.

RAYLEIGH SCATTERING: Scattering by particles very small compared to the wavelength of the radiation being considered. A feature of Rayleigh scattering is that the scattered flux is inversely proportional to the fourth power of the wavelength.

Thus, in the visible region, blue light is scattered more strongly by the molecules of the air than longer wavelengths, accounting for the blue color of the sky.

RAY TRACING: The mathematical calculation of the path traveled by a ray through an optical component or system.

REFRACTION: The bending of oblique incident rays as they pass from a medium having one refractive index into a medium having a different refractive index.

REFRACTIVE INDEX, n (DIMENSIONLESS): The ratio of the velocity of light in vacuum to the velocity of light in the refractive medium. n is a function of wavelength.

RESPONSIVITY, (amps/watt or volts/watt; sometimes called sensitivity): The ratio of the rms value of the output current or voltage to the rms value of the incident monochromatic optical power for a photo detector.

SDM: Acronym for space division multiplex.

SEMICONDUCTOR: A material with electrical conductivity intermediate between that of an insulator and a metal.

SEMICONDUCTOR LASER: A laser in which lasing occurs at the junction of n-type and p-type semiconductor materials.

SHOT NOISE: There is often a (minor) inconsistency in notation when referring to shot noise in an optical system. Many authors refer to shot noise loosely when speaking of the mean square shot noise current (amp^2) rather than a noise power (watts).

Shot noise is caused by current fluctuations, due to the discrete nature of charge carriers and random emission of charged particles from an emitter. The mean square shot noise current is equal to 2qIB where B is bandwidth and I is the average photocurrent. In a photodetector, I contains contributions due to the signal current, background radiation induced photocurrent and dark current. This mean square shot noise current (amp^2) is converted to noise power (watts) in the equivalent resistance of the photodetector and the output circuit.

Notice that shot noise current would reduce to zero if the magnitude of an individual charge (q) tended to zero. This fact reflects the underlying cause of shot noise: the discrete nature of the charge.

If one could somehow eliminate dark current and background radiation on the detector, so the only contribution to

average photocurrent I was due to the optical signal, the resulting shot noise current density would produce noise which is the lower limit on detector noise; this leads to quantum noise limited sensitivity. This term is understandable since the quantum limit to optical sensitivity can also be thought of as being due to the granularity, or particle nature, of light. According to this particle nature, the minimum energy increment of an electromagnetic (optical) wave is $h\nu$ (see the definition of photon).

The term "quantum noise" is often used when referring to the shot noise of the photocurrent due to the optical signal. Thus, quantum noise becomes $h\nu B$ in the limit when photocurrent is due only to the optical signal.

SINGLE MODE FIBER: A fiber waveguide for which only one mode will propagate.

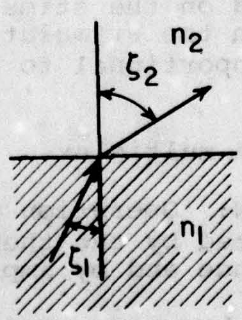
SKEW RAYS: A ray which is skew to the fiber axis. If the fiber waveguide is straight, a skew ray traverses a helical path along the fiber, not crossing the fiber axis. A skew ray is not confined to the meridian plane.

SLD: Acronym for superluminescent diode.

SNR: Acronym for signal to noise ratio.

SNELL'S LAW OF REFRACTION: The law which describes how a ray is bent on passing from one medium to another (see the accompanying figure). In particular,

$$n_1 \sin \zeta_1 = n_2 \sin \zeta_2 .$$



SPECTRAL WIDTH: The wavelength interval in which a radiated spectral quantity is not less than a prescribed part of the maximum; often defined as the rms value

$$\left[\int_0^{\infty} d\lambda(\lambda-\lambda_o)^2\, S(\lambda)\right]^{1/2}$$

where $S(\lambda)$ is the spectral distribution and λ_o is the center wavelength.

SPECTRAL RADIANCE ($W/sr/m^2/\mu m$): Radiance per unit wavelength interval.

SPONTANEOUS EMISSION: Radiation emitted when a quantum mechanical system drops spontaneously from an excited level to a lower level. This radiation is emitted according to the laws of probability without regard to the simultaneous presence of similar radiation. The rate of spontaneous emission is proportional to the Einstein "A" coefficient and is inversely proportional to the radiative lifetime.

STEP INDEX PROFILE: Describing conditions when the refractive index changes abruptly from the value n_1 to n_2 at the core-cladding interface.

STERADIAN (Sr): The unit solid angular measure, being the subtended surface area of a sphere divided by the square of the sphere radius. There are 4π steradians in a sphere. The solid angle subtended by a cone of half-angle θ is $2\pi(1-\cos\theta)$ steradians.

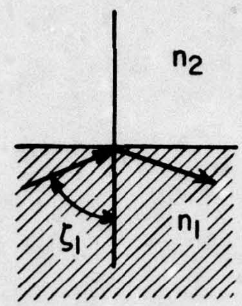
STIMULATED EMISSION: Radiation similar in origin to spontaneous emission, but determined by the presence of other radiation having the same frequency. Since the phase and amplitude of the stimulated wave depend on the stimulating wave, this radiation is coherent with the stimulating wave. The rate of stimulated emission is proportional to the intensity of the stimulating wave.

TDM: Acronym for time division multiplex.

THERMAL NOISE LIMITED OPERATION: Operation wherein the minimum detectable signal is limited by the thermal noise of the detector and load resistance and by amplifier noise.

TOTAL INTERNAL REFLECTION: Light propagated in a medium toward a boundary with a medium having a smaller index of refraction is totally reflected if the angle of incidence (i.e., the angle between the direction of propagation and the normal to the surface) exceeds the "critical angle". The value of this critical angle is given by the relation $\sin \zeta_1 = n_2/n_1$,

where n_2 is the index of refraction of the second medium and n_1 is the index of the first (see the accompanying figure, and also CRITICAL ANGLE).



WAVEGUIDE DISPERSION: That part of the total dispersion attributable to the fact that the critical dimensions of the waveguide, in wavelengths, are a function of frequency.

WDM: Acronym for wavelength division multiplex; see FDM.

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This document has been prepared as a handbook applicable to the design and performance evaluation of optical fiber communication systems. It is oriented toward the communication engineer who is familiar with microwave systems (both cable and propagating), but who has had little or no experience in the fiberoptics technology.

Introductory material for all of the components currently being applied to this new communications technology has been included, together with a discussion of the most important operational parameters and considerations. Contents of the text material have been limited by using a "need to know" concept in order to provide the user with only the necessary and fundamental information.

Design methods are presented in detail, and are coupled with illustrative examples. The methodology presented should be useful as a guideline either to the desing and specification of a system, or to evaluate a proposed design to meet specified operational requirements.

16. Key Words *(Alphabetical order, separated by semicolons)*

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